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PHYSICS
OF
LUBRICATION

A symposium held jointly by the British Rheologists' Club
and the Manchester and District Branch of The Institute of Physics
in Manchester from 29 June to 1 July 1950

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Editorial Note

In the past few years the Manchester and District Branch of The Institute of Physics has held an annual two- or three-day meeting on some branch of applied physics with the object of bringing together those working on the subject in industrial, government and university laboratories. Two of these symposia have been published by the Institute in its *Physics in Industry* series—*Magnetism* in 1938 and *The Measurement of Stress and Strain in Solids* in 1948. With the establishment in 1950 of the *British Journal of Applied Physics*, the Board of The Institute of Physics decided that, in future, symposia of this nature would more appropriately appear as Supplements to that Journal (or occasionally the Institute's *Journal of Scientific Instruments*), reserving the *Physics in Industry* series for specially commissioned monographs.

This first supplement contains the papers presented at a symposium arranged jointly by the Manchester and District Branch of The Institute of Physics and the British Rheologists' Club (now the British Society of Rheology) held in the University of Manchester from 29 June to 1 July, 1950. The discussion printed here is substantially that which took place but has been edited and where necessary revised by the speakers themselves.

I wish to record my grateful thanks to the referee, who prefers to remain anonymous, for his expert advice, to the authors for revising and often reducing their scripts, and to Unwin Brothers Ltd., The Gresham Press, for their co-operation and support at every stage of the production of this first supplement.

The result, it is hoped, is a clear and concisely written progress report on a typical branch of applied physics involving both studies in fundamental physics and empirical work, the practical benefits of which have already been widespread and important both technically and economically. The committee which issued the invitations to read papers could not attempt to cover all aspects of this vast subject in the limited time, but the papers presented, all of which are printed here, well illustrate the enormous advance made since the study of lubrication passed beyond the interest in trials of different oils and greases.

H. R. LANG

Institute of Physics, London
January 1951

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to

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being

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PART 1

Hydrodynamic lubrication and the rheology of lubricants

Hydrodynamic lubrication: general survey

By Professor D. G. CHRISTOPHERSON, O.B.E., Ph.D., A.M.I.C.E., A.M.I.Mech.E., Mechanical Engineering Department, University of Leeds

The subject of hydrodynamic lubrication has now a history of sixty-four years. It was in 1886 that Reynolds' classical paper(1) laid down the main outlines of the subject in explaining the striking results of Beauchamp Tower's experiments, and almost all the work which has since been done on hydrodynamic lubrication stems more or less directly from their work.

That paper enunciated for the first time the principle that the load-bearing capacity of a fluid-film was due to pressures developed when the lubricant was drawn through a constriction or convergent wedge-shaped space under the action of viscous forces, and that accordingly wherever the geometry of the bearing permitted the formation of such a wedge, hydrodynamic forces would appear.

It is of interest on an occasion like the present to try to imagine what the situation would have appeared to be to an intelligent man reading Reynolds' paper on the day it was published, and what such an observer might have considered to be the probable future development of the subject. He would no doubt have supposed that what discrepancies there were between theory and experiment arose because the experimental conditions were not as yet quite what was envisaged in the theory. He could with confidence have anticipated that some of the purely mathematical problems which Reynolds did not attempt, such as, for example, the question of side leakage, would in due time be solved, if not analytically then by an experimental analogy, such as appeared in the Kingsbury electrical tank. It would be asking too much of our observer to suppose that he would have had the mechanical genius necessary to envisage the possibility of the tilting pad thrust bearing, but at any rate, if provided with the necessary drawings, he would have been able, after some fairly elementary analytical work, to prove that the arrangement was theoretically feasible. Perhaps he would have had some doubts (as Reynolds himself must have had) about the nature of the boundary conditions to be imposed in regions where the theory blindly applied led to the conclusion that the pressure in the lubricating film would be large and negative, but he might well consider that a detailed examination of the flow conditions in this region would clear the matter up. Furthermore, it was to be expected that the theory could readily be extended to cover cases in which the load and the film thickness varied with time, or in which the direction of the load was alternating or rotating. There can have been few doubts about the validity of Reynolds' work provided that it was possible to limit operating conditions to the range with which he was primarily concerned.

Let us remind ourselves of the assumptions on which Reynolds' paper was based. In doing so, we may divide them into two classes—those which were quite fundamental and without which any progress could have been made on the basis of general hydrodynamic theory only with extreme difficulty, and those which were useful in that they made the mathematical work much easier, but which were not nearly so essential. In doing so let us recognize that we are really concerned with determining the limitation of the theory in the direction of very heavy load, very thin films, and practical rather than ideal mechanical conditions.

BASIC ASSUMPTIONS OF LUBRICATION THEORY

There is first an assumption universally made and, I think, universally true which does not fall clearly into either of these categories, that fluid velocities perpendicular to the solid surfaces bounding the lubricating film are negligible compared with those in the sliding plane, and a related assumption, that the velocity gradient through the film is very large compared with other velocity gradients.

In the "essential" category, we have three or perhaps four assumptions:—

(1) That the inertial forces due to the density of the lubricating fluid are negligible. This assumption, perhaps the most striking of all, has been questioned many times, and it may well be in certain very high-speed applications it is untrue. But I do not think that any of many anomalous types of behaviour which occur have ever been definitely traced to this source.. Of course, in many cases, for example in the full journal bearing, the inertia forces could be quite large without making any appreciable contribution to the result.

(2) That the behaviour of the lubricating fluid can be completely defined in terms of its "bulk" properties, viscosity, density, and that these quantities are single-valued functions of temperature and pressure. As a rider to this assumption, it follows that the fluid very near to the boundary surface has the same properties as elsewhere.

(3) That the geometry of the bounding surfaces is completely known beforehand.

(4) It is an almost but perhaps not quite essential assumption that the temperature should not vary through the thickness of the film.

Plainly, it is assumptions (2) and (3) which really define the limits within which hydrodynamic theory is applicable in the thin-film region. If, as is of course the fact, there is a layer of lubricant on each surface in which quite different considerations apply, and if, as seems probable, under conditions of heavy load, microscopic changes are continually taking place in the geometry of the sliding surfaces, it is only when we consider films which are thick compared with the surface layers, and regions which are large compared with the deforming area, that the hydrodynamic theory can be applied at all.

Let us turn now to the inessential "simplifying" assumptions. It is in the direction of investigating these factors which were left out of account in the original work but which have proved in several cases to be of substantial practical importance that the greatest progress has been made in the past twenty years or so. We have already referred to the question of side leakage. The pioneer work of Michell,(2) the experimental studies of Kingsbury,(3) the extensive computations of Muskat and Morgan,(4) by means of series solutions, and the development of numerical methods such as those employed by Cameron and Wood(5) have between them provided valuable, if incomplete, information relating the load-carrying capacity and friction of a bearing to its length/width ratio. It was not until these results were available that direct quantitative comparison between theory and experiment in practical cases became possible.

PROPERTIES OF LUBRICANT

The effect of temperature.—It was early understood that temperature considerations would be of paramount importance in determining the behaviour of lubricating films, primarily because of the rapid variation in viscosity with temperature of most lubricating fluids, but also—a consideration which has received a good deal of attention in the last few years—because of the thermal expansion of the lubricant (the so-called "thermal-wedge" effect) which is probably partly responsible for the satisfactory functioning of the high-speed parallel-faced thrust bearing, as observed by Fogg.(6) A number of attempts have been made to determine theoretically the temperature distribution over the bearing surface, one of the most recent and complete being Cope's.(7) Such studies have usually concluded that the temperature of the film rises nearly linearly from the inlet to the outlet, and that no serious error is introduced if for theoretical purposes we assume the heating to be exactly linear. A very interesting topic on which little solid progress has been made is the question of whether or not the geometrical changes due to temperature gradients in the metal parts of the bearing, do or do not have any important effects on performance. The fact is that although lubricant temperatures can be fairly easily measured or, indeed, calculated with reasonable accuracy, comparatively little is known about the temperature of the metal in the sliding surfaces, or more particularly about, for example, the difference between the temperature of the sliding side and the pivot side of a tilting pad in a thrust bearing.

The effect of pressure.—Even if the steady rise of temperature of the lubricant as it passes between the sliding surfaces can be readily appreciated and allowed for, there is still an important source of viscosity variation to which attention must be directed, and that is the variation due to pressure. There is still much work to be done to determine the magnitude of this variation for lubricants of practical importance, but if it can be assumed (as seems very often the case) that the ordinary exponential relation between pressure and viscosity is valid, then the task of incorporating this factor in the theory is much simpler than one might have expected and a number of cases have been worked out in detail, for example by Gatcombe.(8) The quantitative effect of the increase in viscosity due to pressure is not enormously great—in an extreme case it may increase the hydrodynamic load carried, for example, between gear teeth by a factor of rather more than two—but the phenomenon has practical significance because of its bearing on the quantity which engineers call "oiliness." It is not possible for anyone to make any statement on this subject without fear of being proved wrong or at any rate contradicted, but perhaps in a symposium of physicists it may be safe to define oiliness as that quantity which determines the lubricating behaviour of an oil when the load is increased or the speed diminished until hydrodynamic lubrication has broken down. Now it is true in practice that oils which have good "oiliness" also have high pressure coefficient of viscosity—Needs(9) has done a lot of work on this subject—but on the other hand it seems plain that under these conditions other properties, for example "boundary lubrication" properties and extreme pressure properties also come in, and these seem on the face of it to have little to do with the pressure coefficient of viscosity.

There are, of course, other ways in which lubricating fluids may differ from the ideal Newtonian incompressible fluid, for example the viscosity may vary with rate of shear, but we shall hear more about this later in this conference, and I shall not endeavour to anticipate, however inadequately, what will be said then.

PROPERTIES OF THE BEARING METAL

Surface roughness.—Turning now from the lubricating film to the bearing metal itself, it is plain that in the last twenty or thirty years there has been something of a revolution in our ideas about the classification of metallic and in particular of machined surfaces, a revolution which is still going on and which was initiated in part because the importance of surface roughness in lubrication phenomena began to be appreciated. When pioneer work at the National Physical Laboratory and elsewhere made possible the detailed observation of such surfaces, with exact quantitative observation of the magnitude of the irregularities upon them, a complete method of bearing design from first principles became for the first time possible. Postulate that the minimum *average* film thickness at which the bearing will run is equal to the sum of the surface roughnesses, perhaps with some safety factor, make due allowance for the effects of side leakage, and of the temperature rise of the lubricant, and Reynolds' theory, applied in journal bearings or in thrust bearings in which by one means or another a convergent film shape is obtained, will enable a very fair estimate of the load carried hydrodynamically to be made. The coefficient of friction in such a bearing will, however, always be larger than the theory suggests, and this discrepancy will increase as the film thickness diminishes.

It is not difficult to obtain an imaginative picture of what is happening in these circumstances. When the film thickness becomes comparable with the magnitude of the surface asperities, hydrodynamic lubrication will break down at those places and times when two asperities happen to be exactly opposed. We can envisage a state of affairs in which part of the load is carried hydrodynamically, and part by almost direct contact between the metallic surfaces, no doubt under conditions of boundary lubrication. The proportion carried under boundary conditions is sometimes referred to as the contact-load ratio. Clearly, if the coefficient of boundary-friction is known, even approximately, it is not difficult to deduce the contact-load ratio from observations of the actual friction in the bearing combined with a knowledge of the theoretical hydrodynamic friction, and the picture thus presented has all the advantages of convenience and simplicity. If we examine this state of affairs more closely, however, it appears that the situation may be not quite so straightforward. For example, if we postulate a particular typical form of asperity and calculate the hydrodynamic pressure which would act upon it at typical practical values of sliding speed and viscosity, we find the pressure generated may far exceed the yield stress of most bearing metals when the film thickness is still substantially more than what one normally considers to be the thickness of a boundary lubricating film, i.e. a moderate number of molecular layers. Apparently, therefore, such an asperity may get flattened down before boundary lubricating conditions can be established near its peak. But we must bear in mind that the load on the asperity is probably of very intermittent character and the strength may be much increased for short duration loads.

The matter is not quite so straightforward as this, as the high pressure is produced only on the upstream face of the asperity, and on the downstream face there is a reduction of pressure and perhaps some cavitation. The conditions of stress near the peak of the mountain are, therefore, complicated with large shear stresses playing a part, and it is difficult to predict what the nature of the deformation will be.

There is no doubt that a great deal of smoothing does go on in the early stages in the running-in process, and the fact that deformation of the metallic surfaces has taken place is by no means proof of metal-to-metal contact or even of the incidence of boundary contact at normal running speeds.

But if it is true that the surfaces can be smoothed by hydrodynamic forces only, it is not quite so easy to explain the discrepancy between observed and predicted friction at moderate loads in normal cases. Perhaps some explanation may be found in the fact that, whereas theory almost of necessity implies an unchanging regime, in practice, of course, the flow pattern is continually varying as the surface irregularities cross and recross one another. Such a continually fluctuating flow necessarily implies greater losses than a uniform flow, and as the film thickness gets thinner and thinner such fluctuations will come to represent a larger and larger proportion of the total flow.

Direct evidence of the importance of surface finish in fixing the load-carrying capacity of bearings has recently been obtained by Salama.(10) He was concerned mainly to observe the effects of known and deliberately imposed waviness in the surface, but plainly much of his work is applicable in broad outline to accidental irregularities.

General deformation.—Apart from the effect of load in changing micro-structure, there may be a much larger effect in deforming the geometry of the bearing as a whole. For example, a shaft running in a complete journal bearing with clearance and always loaded in the same direction will tend, as has been demonstrated by Clayton,(11) to dig a "pit" for itself, the radius of which conforms more closely to the radius of the shaft. The material in the "pit" is removed probably in part—the largest part—by actual wear, in part by plastic flow of the bearing metal, and in part by elastic deformation which will be recovered when the load is removed. The phenomenon can be understood and its effects predicted in the general qualitative way fairly simply—the deformation will in almost all cases tend to increase the load capacity of the bearing by increasing the "conformity radius," and thus a bearing which at first runs under boundary conditions may "run in" to a state of affairs in which the load is carried hydrodynamically. Almost no quantitative theoretical work on this subject is so far available, though some attempts are, I believe, being made at the present time. Plainly the problem is an extremely difficult one, the exact geometric shape of the film affects the hydrodynamic pressure in it in a very critical way, and the pressure also affects the shape of the film. In neither case is the relationship simple, and in both cases a modification of one condition (pressure or deformation) at a single point affects not only the other condition at that point but also at every other point in the film. It may well be that except in one or two very simple cases, progress in analysing the effect of bearing distortion must be sought solely on the experimental and empirical side. In his recent survey to the New York Academy of Sciences, to which I wish particularly to express my indebtedness, Blok(12) draws attention to the possibilities of employing dimensional methods in the analysis of these complexities, and many of the others to which I refer.

THE NEGATIVE PRESSURE (CAVITATION) PROBLEM

I must now return to a subject to which a passing reference has already been made—the question of the occurrence of negative pressures and cavitation. The complete elementary theory (which a regrettable insularity prompts me to identify when difficulties arise with the name of Sommerfeld rather than Reynolds) plainly predicts that unless the lubricant can always be supplied either at the point of minimum pressure in a journal or under high pressure, large negative pressure will be necessary to maintain a continuous fluid film, and cavitation will in all probability occur. That cavitation does in fact occur can be observed directly by using transparent bearing materials or otherwise,(13) though the limiting conditions under which it occurs are still perhaps somewhat shadowy. But what happens in the cavitating region is still indefinite. Presumably the cavity is filled with a foam in which the bubbles contain gases originally dissolved in the oil, and oil vapour. Presumably also the viscosity of such a foam is much less than that of the continuous fluid, and some reduction in the fluid friction may, therefore, result. The most important result of the occurrence of such cavities, however, may well be that referred to by Shaw and Macks(14) in their recent book. In the normal course of events a particular bubble will travel round the bearing until it comes to the place at which the pressure begins to increase. It will then recondense more or less slowly. But suppose that due to the fact that the load on the bearing is pulsating or varying rapidly, the bubble finds itself suddenly in a region of high pressure. Such conditions would be ideal for the occurrence of the phenomenon of cavitation erosion, and it may well be that some cases of bearing erosion are caused in this way. Moreover, apart from the "bulk" cavitation which may occur over an appreciable part of the bearing arc, there is the possibility of local minute cavitations taking place with similar bad effects on the downstream side of the microscopic surface irregularities to which we have previously referred. The formation of such small cavities in a region of general positive pressure would be resisted by surface tension and it may be that they do not occur, but are replaced by some form of eddy flow.

Perhaps in what I have said I have been inclined to take the engineer's point of view, and to be critical of theoretical argument which, while providing a correct qualitative explanation for the phenomena observed, cannot be employed for design purposes. So let us pass on to the consideration of observations for which it seems to me no really convincing theoretical basis whatever, even of a qualitative kind, can be found.

To one such case we have already referred—the case of the parallel-sided thrust bearing, of which much the most complete experimental survey is to be found in Fogg's work, though it has, of course, been known for a long time that such a bearing would carry some moderate load hydrodynamically. The "thermal-wedge" effect to which we have referred is no doubt partly responsible, but it can only be regarded as entirely responsible if we assume that Fogg's bearings were capable of running hydrodynamically with thinner films than experience elsewhere would lead us to expect. It should be mentioned, however, that Blok employs his dimensional argument to show that Fogg's results are not inconsistent with this view. Perhaps this is the right explanation—indeed a plane thrust bearing is evidently one of the easiest type to make and hence is the type likely to be made with the greatest accuracy. Alternatively, as Salama's paper suggests, there may have been a "waviness" in the surface, which produced just the hydrodynamic conditions required.

Another very similar phenomenon is to be found in the case of the hydrosphere, recently investigated by Shaw and Strang.(15) They report that this device can carry a load comparable with that carried on the same area by a convergent film, with a coefficient of friction which is not much more than would occur under comparable conditions in a journal bearing, and undoubtedly suggests the presence of almost pure hydrodynamic lubrication. It is, of course, quite true that if the oil moves in a partly radial direction the film is in fact convergent and the mystery is at an end. The difficulty is to envisage any reason why such movement should take place.

CONCLUSION

I started this survey by referring to the outlook of an observer when the subject was in its infancy. Let me take a risk and, to conclude, try to guess which of the developments which are now taking place will appear to an observer in twenty years' time to have been of the greatest importance. I must here emphasize that I am limiting myself to the field of hydrodynamic lubrication only, and it may be that all such developments will be seen as being of small importance compared with the studies now going on on the very small-scale (molecular) behaviour of surfaces, and other contiguous subjects. On the engineering side of fluid lubrication only, I should say that two related events of the first importance stand out. The first of these is not a matter of scientific advance so much as of technical education. It has become much more widely realized that very careful attention to the question of ensuring that hydrodynamic conditions obtains wherever possible will give very great returns by way of reduction of wear and longer life, and the necessary knowledge both in design and in such questions as the selection and treatment of lubricants is becoming much more widespread.

Perhaps arising out of this increased appreciation by industry, there is an ever-increasing tendency to demand not that the technique of lubrication in normal bearings should be improved—this is a matter of comparatively small importance—but that more and more types of rolling and sliding contact should be brought within the range of fluid lubrication. I suppose that it is not very long ago that the idea that spur gears could be lubricated under any but boundary conditions except in rare cases would have been considered far-fetched—perhaps it still is. Quite recently, the question of hydrodynamic forces in roller bearings has come to the fore, and obviously the next step applies the same considerations to ball bearings. If, in fact, the "parallel-sided" motion is no obstacle to the establishment of fluid conditions, then what about piston-ring lubrication and so on? Again, can it be that large improvements in metal-working operations such as wire-drawing could be obtained, if by some means the die could be fluid-lubricated? I do not know that these examples, selected at random, are by any means the most important, but they do illustrate that in imagination at least we have come some distance from the state of affairs in which fluid-film lubrication was something that took place in journal bearings and tilting-pad thrust bearings.

I fear that it will appear that I have fallen into one of the pitfalls which always await those who attempt this kind of survey—that in attempting to refer to as many aspects of the subject as possible, I have failed to give an adequate account of any. If this is the case, it has at least this compensation, that all the more scope is available for valuable contributions in the discussion.

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DISCUSSION

Mr. J. A. Cole: I was interested to note that Professor Christopherson included the negative pressure conditions as one of the outstanding difficulties in the understanding of journal bearing operation. This is closely related to the question of film extent, which is of importance when calculating friction torque, and I am wondering whether this matter is really cleared up yet.

The commonly accepted boundary conditions in analyses of journal bearing performance are that the positive pressure film extends from the point of maximum film thickness to a point on the other side (in the direction of rotation) of the point of minimum film thickness determined by $p = \partial p/\partial\theta = 0$. This yields film arcs between 180° and 270°, increasing with decrease of eccentricity.

However, Stanton⁽¹⁾ has reported film extents between 15° and 35° in a full journal bearing of large radial clearance, the film commencing well after the point of maximum film thickness, a result confirmed by later investigators and apparently attributable to an insufficient oil supply. Again, the acceptance of the supposition that the film ends when $p = \partial p/\partial\theta = 0$, with $p = 0$ at the sides of the bearing, precludes the existence of sub-atmospheric pressures, although these have been observed, e.g. by Prandtl.⁽²⁾

I would like Professor Christopherson's views on the adequacy of these boundary conditions in assessing bearing performance, and in particular on their applicability in the analysis of bearings under dynamic loading, where Swift⁽³⁾ used the simpler assumption of a continuous 360° film, with the remark that it was not easy to visualize the periodic rupture and reformation of the film with the rotation of the points of maximum and minimum pressure.

		Heat conductivity in W/m °C at		
		30 °C	*60 °C*	*100 °C*
benzene		0·144	0·137	
naphthalene				0·131
phenanthrene				0·132 at 105 °C
n-hexadecane		0·145	0·140	0·133
n-hexatriacontane				0·169
cyclohexane		0·126	0·120	
decahydronaphthalene		0·113	0·109	0·104
perhydrophenonthrene		0·107	0·104	0·101
mineral oils				
$d_{20°\,C}$ = 0·8644 g/cm³	$\eta_{k\,50°\,C}$ = 263 cs	0·137	0·134	0·130
0·8992	104	0·133	0·131	0·128
0·9202	55·1	0·129	0·126	0·123
0·9140	18·4	0·125	0·122	0·119
Castor oil		0·174	0·172	0·169
Fluoro-carbon oil		0·065	0·064	0·064

Dr. G. W. Nederbragt: Professor Christopherson has stressed the influence of temperature differences on hydrodynamic lubrication. The oil in the wedge is now characterized by the viscosity and by the temperature and pressure coefficients of viscosity. But how about heat conductivity? The differences in the heat conductivities of the hydrocarbon oils are known to be rather small. Yet, from figures obtained by J. W. M. Boelhouwer and myself—with an apparatus of the coaxial cylinder type—it appears that the *ratio* of the heat conductivities of a paraffinic and a naphthenic hydrocarbon may be as high as 1·7.

The heat conductivities of the paraffinic hydrocarbons *n*-hexadecane and *n*-hexatriacontane are relatively high and increase as the molecular weight is higher. The heat conductivities of the naphthenic hydrocarbons cyclohexane, decalin and perhydrophenanthrene are relatively low and decrease as the molecular weight is higher. Looking at other than hydrocarbon oils we find the heat conductivity of castor oil nearly 3 times that of a fluorocarbon oil. What importance is to be attached to such differences in heat conductivity?

Kingsbury⁽⁴⁾ gave in 1933 an example of temperature differences of 15° C and more in an oil film in the direction perpendicular to the surfaces and used in his calculations correspondingly different viscosities. With lower heat conductivity of the oil, the effect would have been still more marked.

Author's reply: With regard to Mr. Cole's remarks, there can, I think, be no doubt that very often the oil film in a journal bearing is formed over a much shorter arc than is theoretically possible. The theoretical distribution should be regarded as an ideal to be aimed at, rather than a standard that can be confidently predicted. Undoubtedly, most of the difference between theory and practice arises from insufficiency in the oil supply, particularly in cases in which the clearance is fairly large.

I do not think we can say at present what is likely to happen under conditions of rotating or alternating load in regions where elementary theory predicts the formation of negative pressures. The conception of a cavity which appears and disappears during each cycle is, as Swift says, not an easy one either to visualize or to deal with theoretically, but it may well be that such cavities do occur and in some cases are not without practical effect on the life of the bearing.

In reply to Dr. Nederbragt, I have no doubt that in cases in which the temperature rise in the oil film is considerable, the thermal conductivity of the lubricant is an important property. Of two otherwise similar oils, that with the higher conductivity is to be preferred.

It might be thought that the temperature rise through the film is controlled by the consideration that as temperature rises and viscosity falls, the rate at which heat is generated also falls. But this argument is fallacious, as any temperature difference through the film produces a redistribution of velocity with larger velocity gradients and shear forces at the hottest points.

Apart from Kingsbury's paper(4) there seems to be very little information about the temperature in the interior of a lubricating film and plainly this is a very difficult, if not impossible, quantity to observe directly.

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The rheology of lubricant films

By E. W. J. Mardles, D.Sc., F.R.I.C., Royal Aircraft Establishment, Ministry of Supply, S. Farnborough, Hants.

The rate of radial spread of a pool of liquid over polished horizontal surfaces or between optical flats, approaching or receding in a normal direction, has been measured for several lubricants and liquid mixtures. The quantitative results obtained have indicated divergences from normal hydrodynamic behaviour and are specific to the kind of lubricant and of the material of the surface.

During the thinning of liquid films, rupturing with "pin holing" has been observed, the stage of onset varying with the kind of surface and lubricant. Evidence of the "wringing" together of flats has been obtained from sliding results at low pressure and by the separation of totally-immersed flats by normal pull with small forces.

The rate of radial spread of a pool of liquid over polished horizontal surfaces or between optical flats, approaching or receding in a normal direction, has been measured for several lubricants and liquid mixtures. The quantitative results obtained have indicated that the radial flow behaviour is not altogether in accord with hydrodynamic theory as Stefan(1) found in 1874. The relevant approximate equation given independently by Stefan, O. Reynolds, and G. I. Taylor for the movement of parallel plates immersed in a liquid is:—

$$d^2 = ct^{-1}F^{-1}, \text{ where } c = 3\pi\eta r^4/4 \qquad (1)$$

and d is the distance between the surfaces after time t, F is the force acting, and r the radius of the plate approaching in a liquid of viscosity η. With a limited quantity V of liquid between the plates the derived equation is approximately:—

$$d^4 = ct^{-1}F^{1}, \text{ where } c = 3\eta V^2/8\pi \qquad (2)$$

Some liquid pools have a curious habit of retracting after a period of spreading or of wandering from the original site. Between flats, after an initial period of spreading, some liquids begin to form a pool with scolloped edges followed by the formation of a filigree pattern and pin holes throughout the pool. It seems that after a period of thinning the film assumes different flow properties due to rupture effects. The onset of these subsidiary events depends on the material of the surface.

Hardy(2) concluded from his "adhesion" experiments with optical flats separated by a lubricant film that orientation of molecules in the thin film caused some measure of rigidity which was dependent on the surface adhesion forces and he wrote: "The influence of the nature of the solid wall is so striking as to make it a matter of surprise that it is not taken into account in certain of the standard methods of measuring the viscosity of liquids." Viscosity values calculated by the author from the rate of radial spread between flats of different materials were found to vary considerably with the material. Again, the shape of the graph relating the film thickness and time was not in accord with Stefan's equation (1) or the derived equation (2), but contained usually a curious bulge, possibly related to the rupture of the thinning film; and the rate of flow became abnormally low when a film thickness of about 5 μ was reached. Similarly, the graph relating the coefficient of static friction with time for a flat slider sinking in a pool of lubricant contains the bulge and confirms the view that the approach of flats occurs in stages. Attempts to explain the anomalies found by Stefan on the grounds of surface roughness have been made by Bikerman.(3) From a variety of tests made to consider this effect and the effect of dust particles, distortion of plates, etc., the author has, however, come to the conclusion that the phenomena observed could not be explained entirely by these causes. In this contribution, the results were obtained with flat surfaces polished under water with fine rouge, rinsed with hot distilled water, dried in air, and finally polished with soft lint. The tests were made immediately following the cleaning and the removal of any dust particles.

RADIAL FLOW OVER A POLISHED HORIZONTAL SURFACE

In the simple case of the radial spread of a pool of liquid over a clean polished horizontal surface, the rate of spread at any time is controlled by the hydrostatic head, the viscosity and the surface tension forces at the boundaries. By measuring from time to time the diameter of, say, a 1 ml circular pool or its area by a planimeter, the relation between the rate of radial flow and the height of the pool may be plotted or a complete

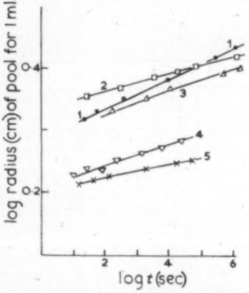


Fig. 1. The radial spread of B.P. liquid paraffin over: (1) glass, (2) aluminium alloy, (3) aluminium, (4) stainless steel, (5) brass

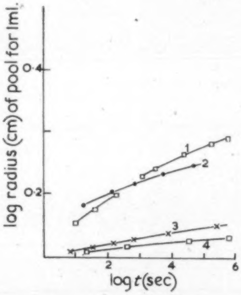


Fig. 2.—The radial spread of B.P. castor oil over: (1) aluminium alloy, (2) glass, (3) brass, (4) sodium stearate

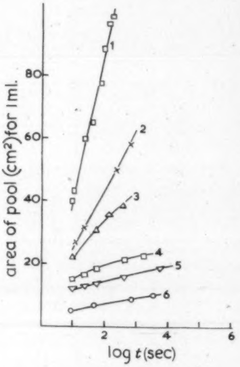


Fig. 3. The radial spread over brass of the following alcohols: (1) iso-propyl, (2) *n*-amyl, (3) *n*-hexyl, (4) *n*-butyl, (5) benzyl, (6) methyl

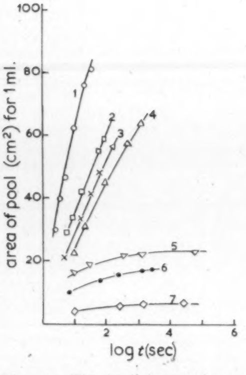


Fig. 4. The radial spread over aluminium alloy of the following alcohols: (1) methyl, (2) *n*-butyl, (3) *n*-amyl, (4) *n*-hexyl, (5) benzyl, (6) cyclohexanol, (7) glycerol

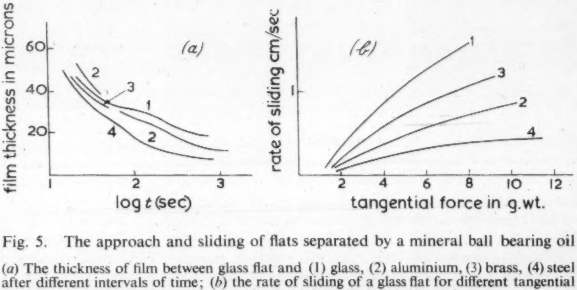


Fig. 5. The approach and sliding of flats separated by a mineral ball bearing oil

(*a*) The thickness of film between glass flat and (1) glass, (2) aluminium, (3) brass, (4) steel after different intervals of time; (*b*) the rate of sliding of a glass flat for different tangential forces on (1) glass, (2) aluminium, (3) brass, (4) steel.

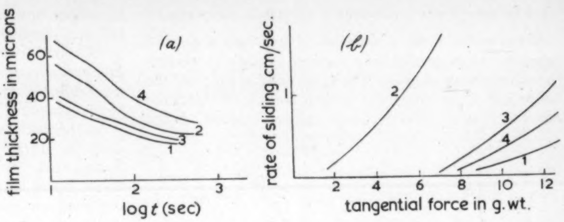


Fig. 6. The approach and sliding of flats separated by a synthetic ester clock oil

(*a*) The thickness of film between glass flat and (1) glass, (2) aluminium, (3) brass, (4) steel; (*b*) the rate of sliding of a glass flat for different tangential forces on (1) glass, (2) aluminium, (3) brass, (4) steel.

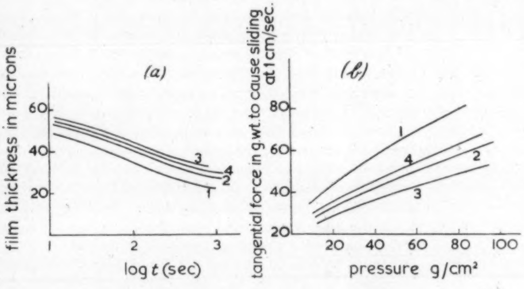


Fig. 7. The approach and sliding of flats separated by a low temperature grease

(*a*) The thickness of film between glass flat and (1) glass, (2) aluminium, (3) brass, (4) steel; (*b*) the relation between tangential force to cause sliding at 1 cm/sec and pressure g/cm² of glass flat on (1) glass, (2) aluminium, (3) brass, (4) steel.

record made of the area or radius of the pool with time. It will be seen from some typical spreading results shown in Figs. 1 to 4 that the surface tension forces are the main controlling forces, and these vary from liquid to liquid and from one surface to another. Thus, for example, B.P. liquid paraffin eventually spreads less on the aluminium alloy than on glass, while a reverse behaviour was found with castor oil. Methyl alcohol spreads relatively little on brass, while on the aluminium alloy the spread exceeds that of the other alcohols. Hydrocarbons and other homologous series of liquid compounds showed similar disparities on different surfaces.

RADIAL FLOW BETWEEN PARALLEL PLATES

With a limited quantity of oil between approaching surfaces the film thickness at any time is approximately proportional to the fourth root of η, F^{-1} and t^{-1}; there are, however, surface tension forces at any discontinuities in the film.[4]

Some results obtained with 0·1 ml of liquid, using a force of 25 g and with 0·5 ml of grease and 1 kg are given in Figs. 5, 6, 7, 8, and 9, where the logarithm of the film thickness or pool radius is plotted against the logarithm of the time elapsed.

Where, under corresponding conditions, with change of material, the rate of radial flow had decreased, the ease of sliding increased (Figs. 5, 6, and 7,).

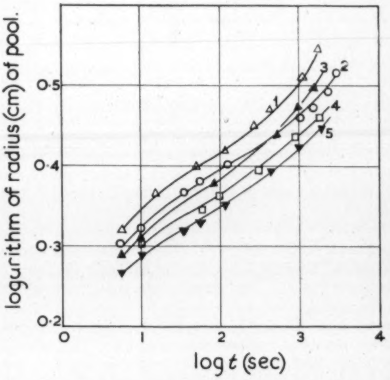


Fig. 8. The radial spread of an anti-seize grease 0·5 ml between glass, 1 kg.wt, and (1) brass, (2) glass (3) cellulose nitrate film, (4) mild steel, (5) cellulose nitrate and cellulose nitrate

In Fig. 10 is indicated deviation of flow rates from the theoretical, of castor oil between glass plates with different loads.

FILM THICKNESS BETWEEN SLIDING SURFACES

When a flat slider is allowed to sink into a pool of lubricant the tangential force required to begin movement increases as time elapses. The curve relating time and the reciprocal of the tangential force is comparable with the curve relating the film thickness and time elapsed. Some results are shown in Fig. 11. Further data obtained with castor oil between glass flats at different pressures are shown in Fig. 12. The graph relates μ_s and time elapsed, each reading being taken with a fresh pool. The results are of some interest because they indicate the limitation of Amontons' law, at the lower pressures. This behaviour of high coefficients at low pressures appears to be associated with the "wringing" together of optical flats.

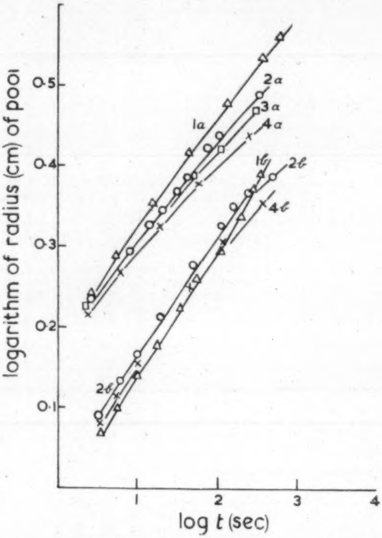


Fig. 9. The radial spread of B.P. castor oil at 20° C, 0·1 ml, between glass and (*a*) with a weight of 525 g on (1) brass, (2) glass, (3) steel, (4) chromium; and (*b*) with a weight of 25 g on (1) brass, (2) glass, (3) steel, (4) chromium

THE SEPARATION OF OPTICAL FLATS TOTALLY IMMERSED

Evidence of surface adhesion forces presumably acting across points of contact between optical flats separated by a film of liquid has been obtained by studying the rate of separation of flats totally immersed. By suspending the upper flat from the arm of a chemical balance, insulated as far as possible from vibration, small forces were applied to lift the flat and the time to break-away was measured. This technique of measurement differs from that used by Hardy, who measured the "instantaneous" break-away load.

Although the method of experiment differs from that used by Hardy(2) in his "adhesion" experiments, his finding that the "adhesion" of two optical flats, other things being equal, depend on the material of the flat has been confirmed. The movement of separation under small forces has been observed microscopically and the curve relating distance moved and time is not in accord with Stefan's hydrodynamic formula, but is more complex and is of the same shape (in reverse) as that found when a pool of liquid spreads radially between two flats. There is a period of little or no movement, followed by a stage of slow steady movement, then a rapid break-away. This is shown in Fig. 13 for castor oil. When the reciprocal of the time of break-away is plotted against the force separating the plates a curvilinear relation is found as shown in Figs. 14(*a*) and 14(*b*) for B.P. liquid paraffin and a grease. The position of the graph varied according to the material of the flats. With the smaller loads the time of break-away becomes exceptionally long, indicating some "wringing together" of the flats.

The problem as to whether thin films contain orientated molecules or whether the boundary layers extends to several molecular thicknesses has not been considered here. There is some evidence, however, in the contribution relating to surface activity and lubricating action(5) that under light loads the boundary layer

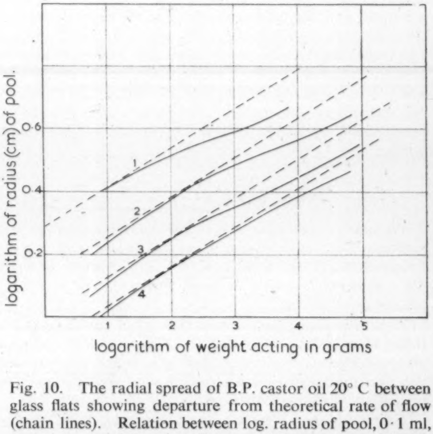


Fig. 10. The radial spread of B.P. castor oil 20° C between glass flats showing departure from theoretical rate of flow (chain lines). Relation between log. radius of pool, 0·1 ml, and log. weight acting (in grams) after (1) 1 000 sec, (2) 100 sec, (3) 10 sec, (4) 3 sec

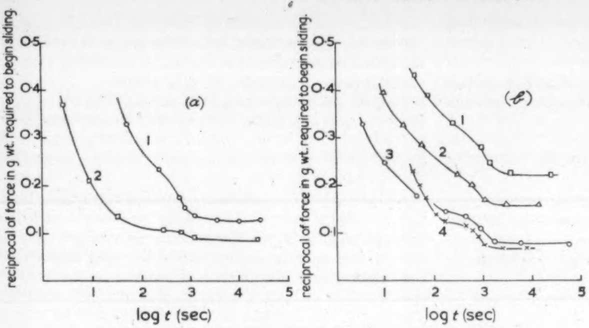


Fig. 11. The relative thickness of lubricant films between flats after different intervals of time, from sliding data. Relation between the reciprocal of force in g.wt required to begin sliding of flat and time elapsed: (*a*) (after Hardy) (1) Bayonne oil between steel flats, (2) *n*-octyl alcohol between steel flats; (*b*) B.P. liquid paraffin between a slider of sodium stearate and aluminium at following pressures in g/cm²: (1) 0·2, (2) 0·5, (3) 2·0, and (4) between glass and glass at 2 g/cm²

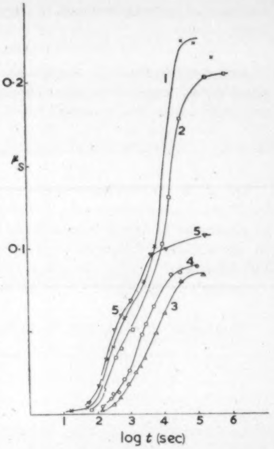
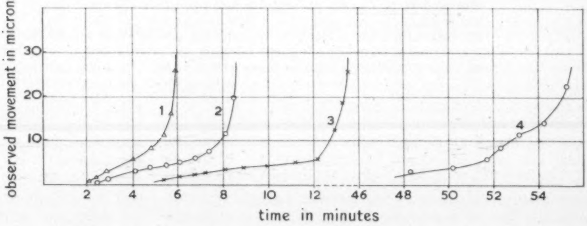


Fig. 12. The relation between μ_s and time for castor oil, flat glass slider on glass, at following pressures in g/cm²: (1) 2, (2) 8, (3) 60, (4) 150, (5) 715

Fig. 13. The movement of parallel plate 3 cm diameter steel disk on glass immersed in castor oil, during separation. Relation between observed movement in microns and time elapsed in minutes with the following forces given in g.wt: (1) 100, (2) 75, (3) 50, (4) 25



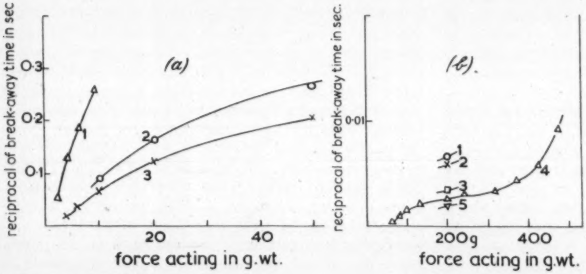


Fig. 14. The relation between the reciprocal of break-away time of parallel surfaces and force in g.wt acting: (*a*) immersed in B.P. liquid paraffin blocks 1 × 3 × 1 cm: (1) aluminium/aluminium, (2) steel/steel, (3) brass/brass; (*b*) low temperature grease between blocks 1 × 3 × 1 cm: (1) steel/brass, (2) steel/glass, (3) brass/brass, (4) cellulose varnish/steel, (5) aluminium/aluminium

appears to extend beyond the mono- or bi-molecular layer.

ACKNOWLEDGMENT

Acknowledgment is made to the Chief Scientist, Ministry of Supply, for permission to publish this contribution to the Symposium.

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DISCUSSION

Mr. J. R. D. Walker: One explanation of hydraulic lock* was that oil films $\frac{1}{4000}$ in thick in some way solidify at pressures of 1 000 lb/in^2. This seems to correspond to the sudden change of rate of spread indicated by Dr. Mardles.

Author's reply: Films do sometimes appear to gell.

No one has yet satisfactorily explained hydraulic lock, but it does appear to be directly connected with the anomalous flow of thin films. The anomalous flow is due in part at least to the instability and rupture of the thinning film. Its onset is dependent on the relative specific character of the liquid and surface material. The liquid film during thinning seems to lose its ability to wet and adhere to the surface.

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* TOWLER, F. H. *Proc. Inst. Mech. Engrs*, **160**, p. 536 (1949).

Viscosity of lubricating oils at high rates of shear

By A. F. H. WARD, M.A., Ph.D., F.R.I.C., S. M. NEALE, D.Sc., and N. F. BILTON, M.Sc.(Tech.),*
Faculty of Technology, University of Manchester

Viscosity coefficients of lubricating oils have been measured, using a high-speed rotational viscometer, with a very thin oil-film. Special attention was given to the estimation of the temperature of the oil, so that the fall in viscosity caused by the rise in temperature might be allowed for. It was then found that at high rates of shear the coefficient of viscosity showed a decrease which was a function both of the rate of shear and of the temperature. This could be interpreted in terms of a balance between the orientation produced by the velocity-gradient and the disorientation caused by Brownian motion. A much more marked anomalous effect was shown when a viscosity-index improver was added to the oil.

During the last thirty years there has been much speculation on the effect of high velocity-gradients upon the coefficient of viscosity of lubricating oils. Although viscosities at high rates of shear have been low, these experimental conditions have given a large production of heat. The fall in viscosity due to the rise in temperature has been of the same order as the fall observed experimentally, and it has therefore been difficult to decide whether the high rate of shear has itself caused any anomalous drop in the coefficient of viscosity. In the present work, an attempt has been made to obtain a sufficiently accurate estimation of the oil temperature to allow for the thermal effect.

Anomalous viscosity has been reported for many colloidal and macro-molecular systems(1, 2) and has been interpreted by Robinson(3) in terms of a balance between the disorientation caused by Brownian motion and the hydrodynamic orientation produced by the velocity gradient. It has been suggested(4, 5) that liquids which are Newtonian at low rates of shear may show an anomalous viscosity at sufficiently high rates of shear. Bondi(6, 7) has suggested that lubricating oils should show anomalous viscosity at a critical shearing stress of approximately 5×10^5 dyne/cm^2. Kyropoulos(8) was the first to investigate lubricating oils at high rates of shear by means of a rotational viscometer. At velocity-gradients of the order of 5×10^4 sec^{-1}, he claimed a reduction in viscosity of about 15% for a number of oils, although the design of his apparatus made the necessary thermal corrections larger than the observed anomaly. Kingsbury(9) claimed that falls in viscosity at shearing stresses of the order of 5×10^5 dyne/cm^2 could be satisfactorily explained by his graphical thermal corrections. The discrepancies reported by Spiers(10) in oil-flow in journal bearings were interpreted by Neale(11, 12) in terms of anomalous viscosity of the oil at the high rates of shear encountered (of the order of 10^6 sec^{-1}). Further, Neale detected birefringence when oils were expelled from capillary tubes by a high pressure. Hagg(13) carried out experiments with light mineral oils in a viscometer very similar to the one used in the present work, but found that the drop in viscosity could be accounted for by means of his analytical thermal theory. Morris and Schnurmann,(14, 15) with a jet viscometer, found a reduction in the viscosity of castor oil by almost 25%.

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* Now at The Vigzol Oil Company, Ltd., London.

It is clear from this review that although large and well-authenticated falls in viscosity at high rates of shear have been established for solutions of macro-molecular substances in oils, there is considerable divergence in the experimental evidence relating to ordinary lubricating oils. The present paper describes a further attempt to discover whether lubricating oils show a fall in viscosity at high rates of shear, after proper allowance has been made for the rise in temperature.

DESCRIPTION OF APPARATUS

It was considered that a rotational (concentric cylinder) type of viscometer, with a very small clearance, would be most appropriate, since a high rate of shear could be obtained with uniform conditions throughout the oil-film. Temperatures and temperature gradients could be measured in the metal on each side of the oil. Both rotor and stator were given a very slight taper, of 0·0042 on the diameter, so that the clearance could be adjusted by moving the rotor axially with respect to the stator. The rotor was 6·38 cm in height, with a diameter at the top of 4·4577 cm and at the bottom of 4·4310 cm. The bearing surface of the stator was 9·93 cm deep, with top and bottom diameters of 4·4661 cm and 4·4247 cm, respectively. The tapers were uniform and the dimensions at all points were accurate to within 0·0001 cm. Both rotor and stator were made from specimens of the same piece of Invar-type non-expansible steel, and the bearing surfaces were carefully ground and finely polished. The stator was surrounded by a water-jacket. The construction of the apparatus is illustrated in Fig. 1. Supports and driving gear are not included.

The water-cooled stator was attached to the base-plate of the instrument by means of a self-centring ball-race at its lower end, and the instrument itself was mounted on the base-plate of a modified drilling machine. The lower end of the shaft of the drilling machine was connected to the rotor through a universal ball-joint. Since the supports of both the rotor and the stator had freedom to move, the rotor automatically assumed a central position in the stator during rotation. The shaft was driven by means of a 6 h.p., d.c. motor, secured at the back of the drilling machine, with a V-belt drive and triple-groove pulleys. This arrangement gave rotor speeds up to about 5 000 r.p.m., measured by a precise electrical tachometer. The whole apparatus was brought to bench height by being mounted on a pile of concrete paving-blocks, alternating with layers of cork. The torque induced on the stator during rotation of the journal was measured by two spring-balances attached tangentially to the drum of the water-jacket by means of strong twine which was wound round a groove in the drum. The oil was supplied at a constant pressure by a pipe through the cooling-jacket and distributed by means of a circumferential groove, 5 mm wide, cut in the inside of the stator. The supply of cold water to the cooling-jacket of the stator was through long pieces of flexible rubber tubing. The inlet water was led through a number of jets directed against the outer surface of the bearing, and the rate of flow was measured. The temperature of both inlet and outlet water was measured at first by mercury thermometers, and later with small wire resistance-coils. From the temperature difference and the rate of flow of water, the rate of heat production was calculated.

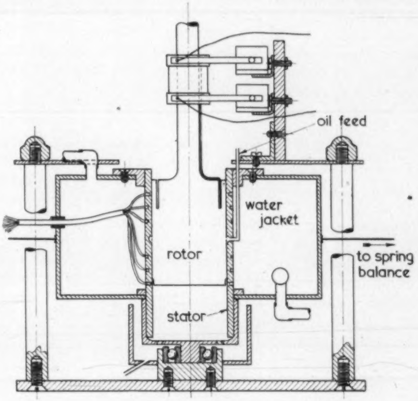

Fig. 1. Diagram of rotational viscometer

MEASUREMENT OF BEARING TEMPERATURES

When heat is liberated in the oil-film during shearing, it passes both inwards into the rotor and outwards through the stator into the cooling-jacket. When an equilibrium flow state is reached, the temperature may be expected to be uniform throughout the rotor, with a value equal to that of the inner surface of the oil-film, since the rate of loss of heat from the rotor is relatively very small. There will be a temperature gradient through the stator, proportional to the rate of heat flow outwards. The temperature of the rotor was measured with a copper-constantan thermocouple. The hot junction was at the bottom of a vertical hole in the rotor, lying 3 mm inwards from the curved surface. To prevent any possible vibration at high speeds, a dummy hole of identical dimensions was drilled in the diametrically opposite position. The thermocouple leads were soldered to two slip-rings mounted on an insulating ebonite carrier on the shaft above the rotor. The rings were made of Thesconite, a silver alloy. Brushes of the same material were held in contact with the rings by light springs. The cold junction was in melting ice, and the leads went through a constant resistance to a sensitive mirror galvanometer. The optimum pressure to be applied to the springs was determined under running conditions by noting the setting which gave the least crackling noise in a pair of headphones, when slip-rings, brushes and headphones were connected in series with a 2 V battery. For temperature measurements when the rotor was immersed in a thermostat at a series of temperatures, values correct within the accuracy of the measurement were obtained, both with the rotor stationary and rotating at speeds up to the maximum.

For the measurement of temperatures in the stator, six circumferential grooves, $\frac{1}{16}$ in wide, were cut in the outer surface of the bearing, and numbered from 1 to 6 from top to bottom. The depths of the grooves were: 1 and 6, $\frac{3}{32}$ in; 2 and 5, $\frac{1}{16}$ in; 3 and 4, $\frac{1}{32}$ in, as measured from the outer surface. About five yards of fine copper wire, 48 s.w.g., double silk-covered, was wound in the bottom of each of the grooves, insulated with shellac, and connected with a Wheatstone bridge. Under test conditions the six readings of resistance had to be made within a small time interval and the accuracy was limited to $\pm$ 0·001 Ω, defining the temperature within 0·005° C. With these arrangements the radial temperature gradient could be determined, and also any vertical variation of temperature could be detected.

EXPERIMENTAL PROCEDURE

The experiments were essentially a comparison of viscosity coefficients determined by two different methods: (i) the rotational viscometer for high rates of shear, and (ii) the conventional B.S.S. U-tube viscometers for low rates of shear. Viscosities were normally measured for the temperature range from room temperature up to 120° C. The densities of the test liquids were also measured over the same temperature range.

With the rotational viscometer, no readings were taken until the rotor had been at the required speed for at least twenty minutes. In this way, thermal equilibrium was established and all readings remained steady under the conditions to be studied. Before the start of every series of tests the drilling machine arm was adjusted so as to give the required clearance in the bearing. The extent of the vertical movement was measured with a cathetometer, and hence the thickness of the oil-film was accurately known. The following readings were taken in each of the test runs: speed of rotation; pull on both spring-balances; temperature from rotor thermocouple; temperatures from resistance of each of the six coils around the stator; rate of efflux of cooling-water; temperature of cooling-water at both inlet and outlet; power input from motor (current and voltage). Periodically, the apparatus for the measurement of the various temperatures was re-calibrated. The following values are considered to be the maximum percentage errors in the various observations: rotor diameter, 0·002; stator diameter, 0·002; diametrical clearance, 2; rotor speed, 0·5 (mean); balance readings, 1·0 (mean). From these figures the maximum error in the calculated viscosity can be shown to be about 4% over a viscosity range of at least 0·1 to 10 poises. The rotor temperature was measured to an accuracy of better than 0·5° C, and the stator temperatures to within 0·005° C.

THEORY OF ROTATIONAL VISCOMETER

a = Radius of inner cylinder.
b = Radius of outer cylinder.
h = Height of inner cylinder (i.e. of oil-film).
c = Radial clearance ($= b–a$).
N = Number of revolutions per sec.
Ω = Angular velocity of rotor ($= 2\pi N$).
S = Shearing stress.
R = Rate of shear strain.
T = Couple retarding rotation.

The coefficient of viscosity, η, may be calculated from the experimental variables. If η is not a constant, but depends on the position in the oil-film, it must be replaced by the mean effective oil-film viscosity, $\bar{\eta}$. It may then be shown that:—

$$S = 4\pi abN\bar{\eta}/c(a + b) \tag{1}$$

$$R = 4\pi abN/c(a + b) \tag{2}$$

$$T = 8\pi^2 N\bar{\eta}ha^2b^2/c(a + b) \tag{3}$$

and the power absorbed in shearing the film $= 2\pi NT$ (4)

or power absorbed $= 16\pi^3 N^2\bar{\eta}ha^2b^2/c(a + b)$ (5)

With most of the conventional types of rotational viscometer there is a viscous drag on the flat lower end of the inner cylinder, and an end-correction has to be applied in the calculations. In the present work, the rotational viscometer has a very small clearance and the test liquids are sufficiently viscous to remain virtually within the annulus, so that it is unnecessary to have a pool of liquid in contact with the inner cylinder. An end-correction, therefore, need not be applied.

TEMPERATURES IN THE OIL-FILM

The rate of heat production in the oil-film equals the power consumed [equation (5)]. In the present work the value of the torque is known directly from the pull on the balances, so the heat production is more readily calculated from equation (4), where a knowledge of the viscosity is not required. The use of the water cooling-jacket promotes the transfer of heat radially through the metal of the stator, and it was found that under these conditions almost all the heat which was generated was absorbed by the coolant. The rotor can thus be regarded as virtually thermally insulated, although at large heat flows there may be a significant drain of heat along the narrow shaft.

In a steady state, the rotor will be at the maximum temperature of the oil-film, θ_2, and the inner surface of the water-cooled stator at the minimum temperature, θ_1 (see Fig. 2). In the present viscometer, the values of θ_1 and θ_2 could be obtained from the temperatures measured experimentally. The temperature measured in the rotor gives θ_2 directly, but the determination of θ_1 requires more consideration. The distribution of the resistance coils at various positions in the stator metal allowed the detection of temperature gradients both radially and vertically. It was found experimentally that in addition to the expected temperature gradient outwards through the bearing, there was also a much smaller downward gradient. It appeared that the temperature drop per unit vertical distance was directly proportional to the rate of heat generation, with a proportionality constant which depended on the clearance in the bearing. Graphs of temperature gradient against heat production were prepared for the various clearances used. It was therefore possible to correct empirically all observed temperatures at the various radial positions to the values they would have at a level half-way down the bearing. The corrected temperatures then showed that in all experiments with the same conditions the value of the axial temperature gradient was the same throughout the stator. An axial heat flow has also been reported by Clayton and Wilkie$^{(16)}$ in horizontal bearings.

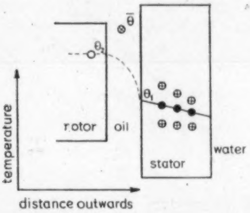

Fig. 2. Distribution of temperature in rotor, stator and oil-film (not to scale)

⊕ Observed temperatures in grooves.
● Bearing temperatures corrected to middle of sheared surface.
○ Rotor temperature, θ_2.
⊗ Mean effective film temperature, $\bar{\theta}$.

The equation for the flow of heat through a bearing gives the temperature drop ($\Delta\theta$) across a thickness t of metal, as

$$\Delta\theta = \frac{Q}{2\pi hK}\log(1 + t/b) \qquad (6)$$

where K is the thermal conductivity of the metal and Q is the rate of heat flow. For small values of t, the equation reduces to:—

$$\Delta\theta = Qt/2\pi hKb \qquad (7)$$

the expression for the flow of heat across a plate. It was therefore possible to obtain an accurate estimate of the temperature gradient across the metal, from the known value of the rate of heat flow. This gave an independent check on the directly measured value of the temperature gradient. Fig. 2 illustrates the relationship between the various temperatures. The observed temperatures in the grooves of the stator were corrected for the vertical temperature gradient to give the points corresponding to the temperatures opposite the middle of the sheared oil-film. These points lay on the line which had a slope equal to the temperature gradient calculated from the rate of heat flow. When this line was produced to the surface of the stator, it gave the temperature, θ_1, of the outside of the oil-film.

Finally, the mean effective oil-film temperature, $\bar{\theta}$, was calculated. The mean effective oil-film viscosity, $\bar{\eta}$, was obtained as described earlier from the readings in the high-speed viscometer. The viscosity-temperature relationship for the oil at low rates of shear had already been found with the U-tube viscometer. The temperature, $\bar{\theta}$, was the temperature to which the oil would have to be raised to reduce the viscosity (at low rates of shear) to the mean value of $\bar{\eta}$ as obtained at high rates of shear. If the calculated value of $\bar{\theta}$ was the same as the mean temperature actually observed for the oil-film in the rotational viscometer, it would indicate that the coefficient of viscosity was the same both for low and high rates of shear. But if the value of $\bar{\theta}$ was higher than any temperature that could reasonably be attributed experimentally to the oil-film, then the coefficient of viscosity at high rates of shear would have to be smaller than its value at low rates of shear. This was regarded as a critical test for anomalous viscosity.

MATERIALS USED

Experiments were carried out with two mineral oils, *A*, a medium oil, and *B*, a light oil, which conformed to the S.A.E. 30 and S.A.E. 20 specifications, respectively. Measurements were also made with mixtures of oil *A* with a polyisobutylene viscosity-index improver, designated P.I.B. P.I.B. was an oil concentrate containing 30% of polyisobutylene of molecular weight 10 000–20 000 in a light base oil. The various test liquids had the following values for density and viscosity:—

	Density at 20° C, g/c.c	*Viscosity at 20° C, poise*	*Viscosity at 80° C, poise*
Oil *A*	0·935	4·22	0·135
Oil *A* + 5% P.I.B.	0·937	6·92	0·204
Oil *A* + 20% P.I.B.	0·924	7·08	0·473
Oil *A* + 60% P.I.B.	0·906	39·8	2·75
Oil *B*	0·944	2·51	0·100

The mixtures with the P.I.B. were used because these might be expected to show an anomalous viscosity even at moderate rates of shear, and the comparison of the results would indicate the reliability of the method.

EXPERIMENTAL RESULTS

Rates of shear up to about 3 to $4 \times 10^5\,\mathrm{sec}^{-1}$ were obtained. As the rate of shear was increased, the shearing stress passed through a maximum (Fig. 3). The fall in shearing stress at high rates of shear was caused by the fall in viscosity (due to the rise in temperature and the anomalous effect) more than counterbalancing the increased speed of rotation [see equation (1)]. It is seen from Fig. 3 that the highest shearing stresses are obtained with the most viscous liquids. The experiments were carried out with radial clearances which were in the range 0·00261 to 0·00342 cm.

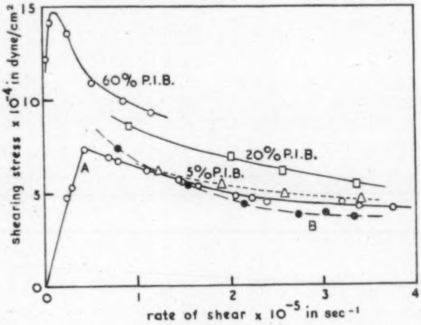

Fig. 3. Shearing stress plotted against rate of shear for the various oils

It has been seen that a critical test for the existence of anomalous viscosity at high rates of shear is that the mean effective oil-film temperature, $\bar{\theta}$, should be greater than the actual mean temperature in the film. The oil temperature varies throughout the film, falling in an outward direction. It might be difficult to decide what temperature, in this range, should be chosen for comparison with $\bar{\theta}$. If, however, $\bar{\theta}$ is found to be higher than the maximum temperature observed in the film (θ_2 at the rotor surface), it will certainly be higher than the temperature at any other point in the film and anomalous viscosity will be established. The experimental results are shown by plotting θ_2 against $\bar{\theta}$ (Fig. 4). Any experimental point which lies below a straight line through the origin at an angle of 45° to the axes shows the presence of anomalous viscosity ($\bar{\theta} > \theta_2$). It should be noted that θ_2 is accurate to $\pm\,0\cdot5^\circ$ C and $\bar{\theta}$ to about $\pm\,1\cdot2^\circ$ C, so that the maximum error in ($\bar{\theta} - \theta_2$) is $\pm\,1\cdot7^\circ$ C.

It is seen that for both oil *A* and oil *B* the curves decrease in slope at the higher temperatures (high rates of shear), and the points lie below the 45° line. The existence of anomalous viscosity is therefore established for these oils. The curves for the mixtures of oil *A* with P.I.B. lie below the 45° line throughout, with a divergence increasing with the percentage of P.I.B. This indicates an anomalous viscosity in all experiments with these mixtures. For oil *A* alone, at the highest rate of shear (about $3\cdot8 \times 10^5\,\mathrm{sec}^{-1}$) the temperature difference corresponds to an anomalous fall in viscosity of about 30%. For the light oil *B*, at a rate of shear of $3\cdot3 \times 10^5\,\mathrm{sec}^{-1}$ there is a viscosity reduction of 20%. For the mixture with 60% P.I.B. the anomalous fall in viscosity is as high as 50 to 70%. The curves for P.I.B. mixtures show a tendency to become steeper at higher rates of shear. This must be attributed to the rise in temperature of the liquid. One would expect from the theory of Robinson[(3)] that at higher temperatures the disorientation of the molecules caused by Brownian motion would become a more important factor and would tend to counterbalance the orientation effect of the velocity gradient.

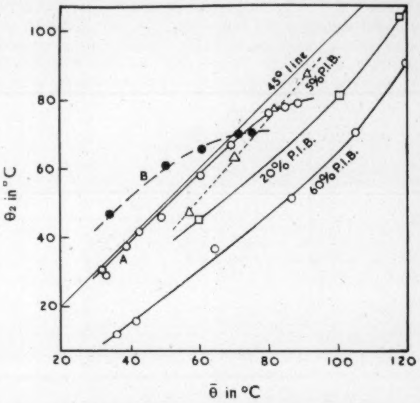

Fig. 4. Maximum oil temperature (θ_2) plotted against mean effective oil-film temperature ($\bar{\theta}$) for the various oils

This effect, caused by a rise in temperature, may be studied by a more detailed analysis of the results with oil *A*. The theory of Grunberg and Nissan[(5)] takes into account the increased freedom of rotation of the molecules at higher temperatures. The extent of the anomaly in viscosity may be expressed by the ratio of the normal viscosity at the temperature θ_2 (η_2) to the viscosity at this temperature for a high rate of shear. Their theory then leads to the result that at a constant temperature the plot of log $\eta_2/\bar{\eta}$ against the rate of shear should give very nearly a straight line for the conditions of these experiments. These straight lines are shown in Fig. 5. It is not possible here to confirm that straight lines are actually obtained experimentally, since for each experiment a different oil-film temperature was obtained. But it is seen that the slopes of the lines decrease systematically with rising temperature. This shows clearly that for a given rate of shear a rise in temperature produces a very marked decrease in the anomalous fall in viscosity.

The theory of Grunberg and Nissan also allows the effect of temperature to be estimated quantitatively. It leads to the conclusion$^{(17)}$ that, with values for the numerical constants appropriate to this oil, the family of lines in Fig. 5 should be brought together into one straight line if log $\eta_2/\bar{\eta}$ is plotted against $(R\eta_2/t^2)(1 + R\eta_2/1\cdot103 \times 10^4 t)^{-1} = \phi(R, t)$, where $t = 273 + \theta_2$. This is shown in Fig. 6. The points now lie very approximately on a straight line. A statistical treatment of these results shows that there is a high correlation coefficient of 0·85 between log $\eta_2/\bar{\eta}$ and $\phi(R, t)$, which is significant at the probability level of 0·002. It is possible that a better line might have been shown if a more accurate estimate could be obtained for the mean actual oil-film temperature. The temperature, θ_2, at the rotor surface was used, and this must obviously be an over-estimate. If a true mean value for the oil-film temperature could have been used, rather larger falls in viscosity would have been obtained.

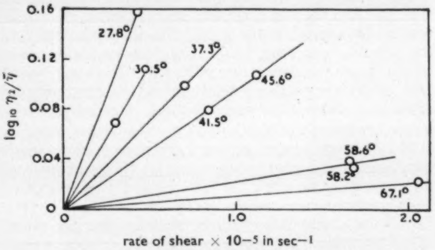

Fig. 5. Log $\eta_2/\bar{\eta}$ plotted against rate of shear

It must also be pointed out that the points in Figs. 5 and 6 relate only to experiments at rates of shear up to about 2×10^5 sec^{-1}. At higher speeds the points in these plots showed large random variations. A possible explanation of this behaviour is that laminar flow is changing over to turbulence. The calculations of Taylor$^{(18)}$ for the onset of turbulence in the flow of liquid in the space between two coaxial cylinders, with the inner cylinder rotating, show that much higher speeds would be needed than were used here. There is, however, the possibility that at these speeds some vibration may be occurring, which would cause an earlier onset of turbulence, as was shown by Fage$^{(19)}$ for axial flow in an annular pipe. It may, therefore, be suggested as a reasonable explanation of the erratic results at the highest rates of shear, that slight vibration caused by the high running speeds may be interfering with the laminar flow on which the theory is based.

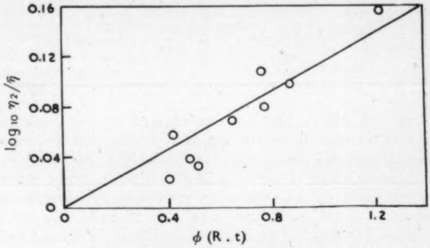

Fig. 6. Log $\eta_2/\bar{\eta}$ plotted against $\phi(R, t)$

Comparisons have been made between the observed drop in temperature across the oil-film $(\theta_2 - \theta_1)$ and the value calculated from the theory of Hagg.$^{(13)}$ A fair, though not perfect, agreement was obtained. Hagg's theory does not account, in terms of thermal effects, for the large values of the mean effective oil-film temperature.

The present work, therefore, indicates that ordinary lubricating oils may show anomalously low viscosities at high rates of shear, and that the fall in viscosity is much more marked in experiments at lower temperatures. This agrees with the theory put forward by Robinson and gives a quantitative confirmation of the equations of Grunberg and Nissan. The anomalous effect was increased by the addition to the oil of a viscosity-index improver.

ACKNOWLEDGMENTS

The authors wish to offer their best thanks to The Vigzol Oil Co., Ltd., which provided materials and made a generous financial grant towards the cost of the apparatus; to Mr. J. C. Balmforth, who helped in the solution of constructional difficulties; and to Mr. T. Bevan, of the Metrology Section of the Department of Mechanical Engineering of the Manchester College of Technology, who very kindly made the precise measurements of the dimensions of the rotor and stator.

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DISCUSSION

Dr. H. Blok: The results obtained by the authors would appear to prove beyond doubt that at least certain straight mineral oils can exhibit a real viscosity fall under rates of shear appreciably lower than those which would correspond to the critical shearing stress of about 5×105 dynes/cm^2 that was theoretically predicted by Bondi.(1) These results need not be considered to be in contradiction with the ones recently found by S. J. Needs in America who, in his experiments for the A.P.I. Sub-Committee on viscosity at high rates of shear, which were carried out in a high-speed viscometer very similar to the authors', found that neither of his two straight mineral oils (a turbine and a transformer oil) showed any real viscosity fall under rates of shear exceeding one million reciprocal seconds, that is, higher than the authors'. In fact, both of Needs's oils were less viscous than the authors'.

In view of the importance of the authors' results, they might be requested to submit such additional physical and chemical data as may give oil experts a better idea about the nature of the two straight mineral oils of the present investigation.

Finally it may be pointed out that, although the authors' method for judging the reality of viscosity falls observed is quite straightforward in all cases where mean effective temperature $\bar{\theta}$ is greater than the temperature θ_2 at the rotor surface, it is no longer unambiguous in cases where $\bar{\theta}$ proves to be smaller than θ_2. In the latter cases this method does, for instance, not permit the assessment of the rate of shear where the real fall in viscosity just sets in; at least for such cases it might be recommended to utilize the method worked out and successfully applied by Hagg,(2) which was later applied too by the present writer.(3) It is felt that the evidence furnished by the authors would become more complete and therefore become even more enlightening, if they would now present it in a diagram, such as suggested for the relevant case of the heat-insulated rotor by Figs. 2 or 3 (case $p = 1$) of my paper(3) and taking the relevant curve for Newtonian oils as a reference; in this connexion it may be noted that the data in the authors' paper are not detailed enough to enable the reader to construct such a diagram himself.

Authors' reply: We should like to thank Dr. Blok for the comments and suggestions which he has made.

The difference between our results and those of S. J. Needs for straight mineral oils may perhaps be attributed to a difference in the experimental conditions. In our experiments, although the thickness of the stator metal was only 0·4 cm and there was water-cooling outside to remove heat as efficiently as possible, the temperature of the oil film exceeded 100° C in runs at high speeds owing to the very great rate of heat production. Needs also refers to heating effects in the oil film, and he apparently did not use water-cooling. Our results show larger anomalous falls in viscosity at low rates of shear (and low temperatures) than at high rates of shear (with the consequent higher temperatures). This is because of the disorientation effect on the long-chain molecules at higher temperatures reducing the anomalous fall. We have shown that this effect of temperature has much more influence than the rate of shear. Since extraordinary precautions would have to be taken to avoid excessive temperatures at very high rates of shear (such as cooling with liquid air, for example), one would expect that beyond some limit the anomalous effect would rapidly decrease with increasing rate of shear.

In view of Dr. Blok's suggestion, more information has been given in the printed paper about the properties of the oils. It has not been possible to include tabulations of all the experimental temperature measurements because of limitations of space. However, the temperature drops across the oil film have been calculated in all cases by the method of Hagg and have been found to agree moderately but not perfectly with the experimental values. This does not affect the validity of our conclusions, since the Hagg theory has not been invoked in their deduction.

We agree that the proof of an anomalous fall in viscosity would be ambiguous in cases where $\bar{\theta}$ is lower than θ_2. Since this would involve theoretical assumptions about the nature of the temperature distribution across the film, we have preferred to base our case for the existence of anomalous viscosity on results where $\bar{\theta}$ is higher than θ_2 and our conclusion is derived directly and unambiguously from experimental measurements.

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The lubrication of cotton and other textiles

By E. Moss, B.Sc., A.R.I.C., British Cotton Industry Research Association, Shirley Institute, Manchester

The frictional properties of cotton are controlled by the layer of natural wax on the fibres. Those finishing processes which remove wax tend to increase friction between cotton and other surfaces. The introduction of other surface layers, as in dyeing, may also increase friction. The high friction of wax-free cotton is reduced by the addition of lubricants, whose effect within some classes of compound varies regularly with chemical constitution. The lubrication of regenerated celluloses is broadly similar. Low and uniform friction between textile and machine is very important in processes such as knitting and stitching.

The lubrication of textiles forms a part of a much larger subject, namely, that of their frictional properties. Friction is of considerable importance at all stages in the manufacture of textiles—inter-fibre friction in drafting and in yarn strength, yarn friction in the processes of winding, weaving and knitting and in tension control, cloth friction in processing and in the handle of finished cloths. All these aspects of textile friction have been studied at the Shirley Institute, but much of the work so far has been on yarn friction, partly because yarns are more convenient to handle than fibres and partly because there is no really satisfactory method of measuring cloth friction. Consequently, this paper is confined largely to yarn friction.

MEASUREMENT OF YARN FRICTION

Two instruments for measuring kinetic yarn friction have been developed at the Shirley Institute.(1, 2) Both are based on the well-known $e^{\mu\theta}$ law connecting the tensions in a thread running round a friction surface. Morrow's instrument gives an autographic record of the coefficient of friction μ along the length of the yarn but has the disadvantage that it is inconvenient to change the friction surface. Buckle and Pollitt's instrument does not give an autographic record but is designed to facilitate changing the shape, temperature and nature of the friction object.

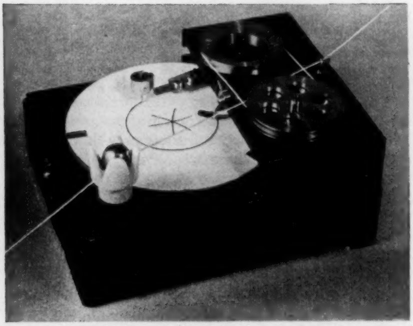

Fig. 1. Modern form of Morrow's yarn friction tester.

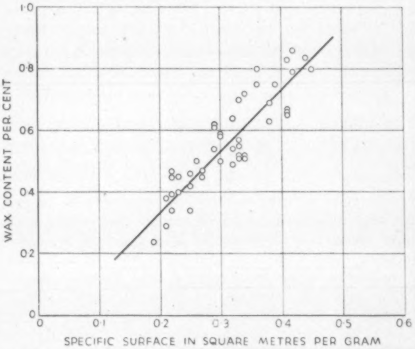

Fig. 2. Relation between specific surface and wax content of different cottons.

With these instruments the speed and initial tension of the yarn can be varied at will but all the coefficients of friction quoted in this paper have been measured at 70 ± 2° F and 65 ± 1% relative humidity with an initial tension of 7–10 g and at a speed of 60 yd/min against mild steel on a modified form of Morrow's instrument (Fig. 1). Although nearly all the measurements have been between yarn and mild steel, friction of cotton against cotton follows closely that of cotton against steel, and it has been possible, therefore, to apply the results to industrial processes involving fibres and cloths and also friction between textile surfaces.

THE NATURAL LUBRICANT OF COTTON

All raw cotton fibres contain a natural lubricant, cotton wax, which consists principally of straight chain fatty alcohols and acids with about 30 carbon atoms.(3,4,5,6) This wax is almost, if not quite, wholly associated with the surface of the cotton hairs;(7,8,9) the amount of wax is, in fact, directly proportional to the specific surface (calculated from the fibre characters by the method of Peirce and Lord(10)) of the cotton (Fig. 2) so that all cotton hairs, coarse or fine, short or long, have a layer of approximately the same thickness on the surface. The amount of wax varies from about 0·2% by weight for the coarsest to about 1% for the finest mature cottons, and as the specific surface is high, this corresponds to a layer only about 5 molecules thick, assuming that the wax is entirely on the surface of the fibres. The difficulty of extracting the wax completely with solvents suggests, however, that a part of the wax may be distributed through the primary wall. It is the presence of this lubricating layer of wax which makes it possible to draft cotton in the normal processes of spinning. All grey cotton yarns have a coefficient of kinetic friction against mild steel of about 0·25 under the conditions of measurement stated above. When the wax is removed by extraction the coefficient of friction rises to about 0·7 and drafting becomes exceedingly difficult.

FINISHING AND WAX CONTENT OF COTTON

In finishing, cotton usually undergoes the processes of scouring with alkaline liquors and bleaching in order to clean it, or to make it absorbent, and these processes inevitably remove a proportion of the natural wax which varies with the severity of the treatments. When the wax is reduced to an amount corresponding to a layer about 2 to 3 molecules thick, friction begins to increase, and when the equivalent layer is less than 2 molecules thick permanently high friction results. Other processes, dyeing for example, may increase friction by introducing other surface layers. High friction is usually, though not always, undesirable in textiles and it is for this reason that lubrication is important. The high friction of wax-free cotton is extremely sensitive to the addition of lubricants, whether they are added deliberately or picked up by contamination. This property is actually used to establish freedom of the friction surfaces from lubricant before each measurement, a cotton yarn freed from lubricant being run through the instrument to clean it until high friction is recorded.

LUBRICATION OF COTTON

The lubricating effects of a large number of substances on cotton have been determined. A few of the results are shown in Table 1, where the lowest value of the coefficient of friction and the least addition of each lubricant required to produce the lowest value are quoted. The amounts of added lubricant were determined by extracting with a suitable solvent and weighing the dried extract.

The coefficient of friction of the well-scoured cotton before the addition of any lubricant is greater than 0·6 and several of these substances reduce the coefficient of friction to below 0·25, the value produced by the natural lubricant cotton wax. There does not seem to be any general relation, however, between the lubricating effect and the chemical constitution, but there may be with some physical property of the lubricants at the higher temperatures occurring at the rubbing surfaces.

Table 1. *Lubricating effects of substances on cotton*

Lubricant	*Lowest value of μ cotton against steel*	*Least addition % to produce lowest value*
Paraffin wax	0·14	0·7
Mineral oil	0·22	0·3
Octadecyl alcohol	0·26	0·1
Stearic acid	0·20	0·4
Oleic acid	0·20	1·0
Ricinoleic acid	0·29	0·15
Methyl stearate	0·15	0·3
Methyl oleate	0·14	1·5
Tallow	0·23	0·5
Castor oil	0·35	0·2
Sperm oil	0·20	1·0
Sodium stearate	0·25	less than 0·1
Sodium oleate	0·26	0·15
Sodium ricinoleate (castor oil soap)	0·33	3·0

Paraffin wax and methyl stearate and oleate are outstanding, so firm attachment of the lubricant to the surface by a polar group is not necessarily a requirement of a good textile lubricant. Castor oil and castor oil soap show up badly. The double bond in the carbon chain of oleic acid seems to have little effect, for there is little difference between the minimum coefficients of friction reached with stearic acid and oleic acid or with their derivatives, although larger additions of oleic acid and the oleates are required to produce the lowest values. An hydroxyl group attached part way along the carbon chain in addition to a double bond as in ricinoleic acid and castor oil does reduce the lubricating effect. Perhaps it reduces lateral cohesion between the carbon chains which may also be important.(11)

Within particular classes of compound certain regular changes in lubricating effect may be noticed (Table 2).

Table 2. *Regular changes in lubricating properties*

Lubricant	*Lowest value of μ cotton against steel*	*Least addition % to produce lowest value*
Lauryl alcohol, C_{12}	0·12	2·0
Myristyl alcohol, C_{14}	0·17	1·5
Cetyl alcohol, C_{16}	0·20	0·25
Octadecyl alcohol, C_{18}	0·26	0·1
Methyl oleate	0·14	1·5
Ethyl oleate	0·16	1·0
Butyl oleate	0·19	2·0
Cyclohexyl oleate	0·23	0·5

The decrease in the addition required to produce the lowest value of coefficient of friction with increasing length of the carbon chain is a common feature. It occurs also with the saturated fatty acids and with their methyl esters

The values in Tables 1 and 2 are obtained from friction/addition curves of which Fig. 3 shows typical examples. Usually there is first a rapid fall in coefficient of friction with addition and the curve then flattens out gradually to a steady value. The values may be somewhat misleading unless it is realized that in comparing lubricants the friction/addition curves may cross, so that at one addition lubricant *A* may give a lower coefficient of friction than lubricant *B*, while at another addition lubricant *B* may give the lower value.

The quantity of lubricant required to produce the lowest value of the coefficient depends to some extent on the distribution of the lubricant. Thus a surface coating of a solid lubricant, for example paraffin wax, produces the maximum decrease at a smaller addition than does penetrative addition, for example in a solvent, where the lubricant is spread throughout the yarn. On the other hand, there is little difference between the effects of additions made from solvents or emulsions or even as an undiluted liquid.

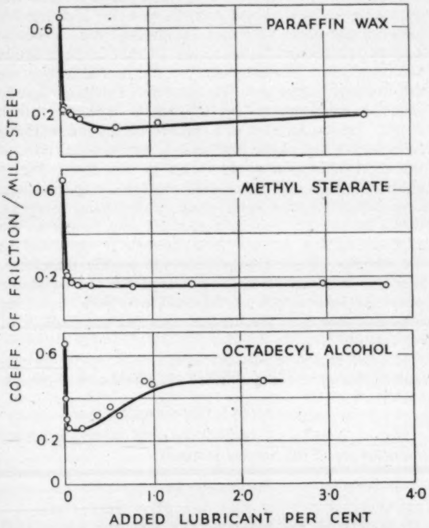

Fig. 3. Effect of lubricants on frictional properties of well-scoured cotton.

Sometimes the coefficient of friction tends to rise again when the quantity of lubricant is increased beyond that required to produce the minimum value; occasionally this effect is very marked.

There are other anomalies for which no satisfactory explanation can yet be offered. Sodium ricinoleate requires a 3% addition to reduce the coefficient of friction to 0·33, whereas other soaps, such as sodium or potassium stearate or oleate, reduce it to 0·25 with an addition of 0·1% or less (Fig. 4). It may be that sodium ricinoleate is absorbed by the cotton fibre and forms a surface layer only when the absorption is complete. This would link up with the well-known softening effect of castor oil soap on cotton yarns and cloths. Again, when soaps are added to well-scoured cotton they reduce the coefficient of friction from 0·7 to about 0·25, but when they are added to unprocessed or mildly scoured cotton they increase it from 0·25 to about 0·35.

SIDE EFFECTS OF LUBRICATION

Lubrication has side effects which may sometimes be undesirable. It can reduce wettability and absorbency, which are of great importance in certain finished textiles, for instance surgical lints. It may also reduce the strength of yarns and cloths by reducing inter-fibre friction. For example, surface addition of paraffin wax to a high friction yarn with low twist reduced its strength by 13%, penetrative addition by 28%. When the surface-waxed yarn was heated for a short time so that the wax melted and flowed into the yarn the loss in strength increased to 34%.

OTHER TEXTILE FIBRES

The effects of lubrication on regenerated celluloses such as viscose are broadly similar. They contain little or no natural wax, but they are usually treated with a lubricant of some kind during manufacture to reduce friction and static electricity charges and to hold the filaments together until twist can be inserted.

KNITTING

In conclusion one or two examples of the uses of lubrication in textile industrial processes may be cited. Knitting is a process in which it is important that friction should be low, for the yarn has to pass round numerous guides and needles and at each the tension increases roughly according to the $e^{\mu\theta}$ law, so that, unless μ is low, very high tensions are progressively built up in the running thread and cause breaks and other defects.

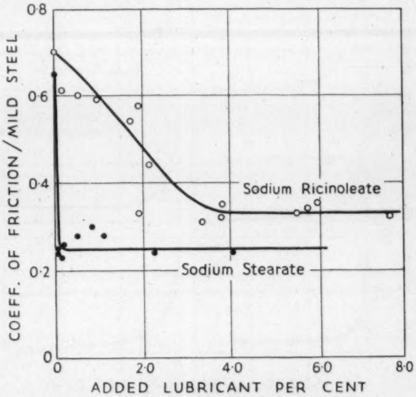

Fig. 4. Effect of soaps on frictional properties of well-scoured cotton.

The sorts of increases in yarn tension that may be expected for different coefficients of friction have been calculated assuming an angle of contact at each guide of 90° (Table 3).

Table 3. *Increase of tension for various values of* μ
$\theta = 90^\circ \; T_2/T_1 = e^{\mu\theta} = e^{1\cdot57\mu}$

	Factor by which tension is increased			
μ	*1 guide*	*2 guides*	*3 guides*	*4 guides*
0·15	1·3	1·6	2·0	2·6
0·25	1·5	2·2	3·2	4·8
0·35	1·7	3·0	5·2	9·1
0·65	2·8	7·7	21	59
$>$0·9	$>$4·1	$>$17	$>$69	$>$286

When μ is below 0·3 the increases in tension are tolerable, but when μ is above 0·3 and particularly when it is above 0·6 the increases in tension are so great that they would almost certainly lead to trouble in processing. If the angle of contact were assumed to be 180° the third column in the table would apply to one guide and the fifth column to two guides. On the other hand, if the angles were 45° the second column would apply to two guides and the third column to four guides.

In knitting it is important that μ should not only be reasonably low, say below 0·3, but also that it should be uniform, for if μ varies the tension varies and the size of the yarn loops varies, giving irregular knitting.

STITCHING

Stitching is another process into which friction enters in a variety of ways. First there is the friction between the sewing thread and the guides round which it passes and between the thread and the eye of the needle. To minimize this, sewing threads are often lubricated by running the thread in contact with a solid block of paraffin wax when they are being wound on to the reel or spool during the last stage of manufacture.

Then there is friction between the needle and the fabric. Ideally, the threads of the fabric should slide apart and allow the needle to penetrate without any damage, but if friction is high the threads cannot move over one another and, as friction is also high between the needle and the fabric, the needle tears and cuts the threads, leading to weakened seams of poor appearance. This defect occurs particularly with mineral khaki-dyed fabrics which have not been suitably lubricated, because the fibres are coated with discrete particles of iron and chromium oxides. These particles produce high friction between the fibres and have an intense abrasive action on the sewing needle, so much so that in high speed stitching it is not uncommon for the needle to become red hot and buckle up. The amount of damage can be reduced considerably by lubrication and a "stitch finish," i.e. the addition of a specified amount of suitable lubricant to the cloth, has become an essential part of the specification for many cloths of this type. Fig. 5 shows the effect of various lubricants on the damage caused to a mineral khaki-dyed cloth during stitching. It will be noticed that the curves are very similar to the friction/addition curves. The damage is expressed as the number of cut threads per 100 needle punctures, which is obtained by making a large number of needle punctures in a square of the cloth and then dissecting the cloth thread by thread and counting the number of cut threads.

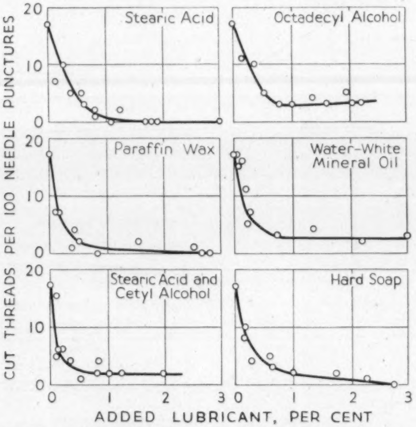

Fig. 5. Effect of lubricants on the damage caused to a mineral khaki-dyed cloth during stitching.

A more complete account of the work on which this paper is based will be published elsewhere in due course.

ACKNOWLEDGMENT

Figs. 1, 2 and 5 are reproduced with permission from publications of the Shirley Institute.

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DISCUSSION

Mr. A. Perelman: I should like to try to reconcile the results given by Mr. Moss, in his paper, of the increase in the coefficient of friction of cotton against steel with the increase in chain-length of the paraffin lubricants; whereas a questioner from Holland claims to have obtained a reversal of this tendency. The figures Mr. Moss gave were the *minimum* coefficients of friction obtainable with each lubricant, beyond which further additions did not improve it. At the same time he gave figures showing that the percentage of lubricant necessary to reach these minima *decreased very sharply* with the increase in chain-length. I believe that in the Dutch experiments the amount of lubricant was the same in each case and I think it is very probable that this amount was less than that necessary to reach the minimum with the short-chain lubricants. In that case the results are in no way contradictory.

Mr. A. A. Milne: One of the items of particular interest in this paper is the complete reversal, in order of increasing friction, between the lubricants used under the conditions described in this paper and the same lubricants when used under conditions more usually quoted for boundary lubrication, i.e. at low velocities, high pressures, and with metallic surfaces. It has been shown by Barwell and Milne* that the conditions under which boundary lubricants are used may have a very considerable effect on the resulting friction. This paper certainly confirms the view that it is impossible to ascribe, as has been done all too frequently in the past, a unique value to the coefficient of friction of any substance, and that full details are always required of the conditions under which values of the coefficient were obtained. It would be interesting to know just what changes in conditions result in this reversal of the order of value of the lubricants quoted in this paper. Has the author investigated the effect of changes in rubbing velocity or of changes in the surface finish, or is it rather the case that lubricants that are, in general, "good" for metallic surfaces are "bad" for textiles?

Author's reply: In comparing the effects of different lubricants it is very important to make use of the whole of each friction/addition curve. It not infrequently happens that the curves cross over so that at one addition lubricant *A* may produce lower friction than lubricant ***B***, while at another addition the reverse is the case. The fatty alcohols, when compared at an addition of 0·1%, give coefficients of friction of 0·29, 0·26, 0·24 and 0·26 for lauryl, myristyl, cetyl and octadecyl alcohols respectively.

It is true that the coefficient of friction varies considerably with the conditions of measurement and I was careful to mention that all the values quoted in the paper were obtained under one set of conditions. It has been found for a number of yarn-surface combinations that the coefficient of friction increases with increasing rubbing velocity. On the other hand, with metal on metal a decrease in friction with increasing velocity is usual. It has also been found that for certain yarn-surface combinations the rougher the surface of the friction object the lower the coefficient of friction. Finally, the subject of textile lubrication is much too complex for any broad generalization at present and I certainly could not subscribe to a general statement that lubricants which are "good" for metallic surfaces are "bad" for textiles.

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PART 2

Boundary layer and extreme pressure lubrication

An introduction to boundary and extreme pressure lubrication

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After indicating the relationship of boundary and fluid film lubrication, and the importance of boundary lubrication, reference is made to the explanations of boundary friction, in particular to the adhesion theory; the simplified explanation of the laws of friction in terms of this theory is given. Dealing with the influence of the main variables on friction values, velocity is first considered, together with the explanation of friction-induced vibrations in terms of the main type of friction/velocity curve; a simple general statement on the effects of temperature and surface roughness on friction cannot yet be given. Brief references are made to the high temperatures reached superficially at sliding contacts, and to electrical effects. In terms of these fundamental conceptions, a sketch is given of the mechanism of running-in, of wear (including notes on wear testing and anti-wear additives), of the behaviour of surfaces under severe conditions leading to scuffing (including the function of extreme pressure lubricants). Finally the value of solid lubricants is mentioned, and also the benefits that can be obtained by chemical pre-treatment of the solid surfaces. At each appropriate point of the survey reference is made to the other papers presented to the Conference.

PREAMBLE

This paper is intended to provide the general background of this part of the subject of lubrication, chiefly for the non-specialist, so that the individual papers can be seen in relation with the whole.

INTRODUCTION

For the general run of sliding contacts the most important property of a lubricant is its viscosity, allowing fluid films to be built up and the solid surfaces to be floated apart. This is the regime that Professor Christopherson dealt with. The friction is due to shear of the fluid layer and coefficients of friction are generally very low (of the order of 0·01 or less in practical cases).

When a solid surface rubs a solid surface and there is no fluid film to take any of the load, the regime is called "boundary lubrication." Under these conditions it is the chemical nature of the lubricant and of the surfaces which is of particular importance, in contrast to fluid film lubrication where viscosity is the important property of the lubricant and no other property of the surfaces but the shape matters.

The designer's aim should be to ensure that a fluid film is obtained, if at all possible, because the friction is then low and ideally there is no wear. There are a number of circumstances, however, which lead to at least a proportion of boundary lubrication obtaining, occasionally throughout the running life of a mechanism, more often at certain periods of its operating cycle. Even with those mechanisms with the most easily formed fluid films, like journal bearings, boundary conditions occur on starting and it is important that there should not be damage of the surfaces before a fluid film is established; the boundary condition very rapidly gives place to mixed conditions and then to a fluid film as the speed increases. Sometimes an inadequate supply of oil leads to boundary lubrication occurring. Moreover, in the fluid-lubricated mechanism it is naturally the aim to increase the load as much as possible in order to make a small mechanism do a big job; the fluid film then becomes thin and the possibility of solid surface contact is increased. In other cases the form of the surface makes it difficult to establish a fluid film, e.g. with the opposed curvature of gear tooth surfaces. If the load is light and the accuracy of the teeth is high a complete fluid film can be established, as has been demonstrated by gears running, under good conditions, for long periods without the removal of their grinding marks. There is inevitably, however, a liability to rubbing.

It is therefore important to understand boundary lubrication phenomena even under conditions classed as good. It is just so much more so when boundary conditions wholly prevail or obtain in substantial measure. The troubles of wear, scoring, scuffing, seizure, etc., all consequences of increasing severity of contacts in boundary lubrication conditions, can only be avoided by positive knowledge.

Reference has been made to the freedom of fluid lubricated surfaces from wear under ideal conditions. Departure in particular is due to particles in the lubricant; wear can obviously occur with nominally fluid lubricated surfaces if particles greater in dimensions than the thickness of the film are present. Indeed it may be said that most wear in practice is due to particle contamination. The trouble is largely avoidable by providing clean lubricants, but for some time, and to some extent inevitably, there will be particles in lubricants. Boundary lubrication research should accordingly deal with the contacts between particles and surfaces as well as contact between the surfaces themselves.

Boundary lubrication is essentially a function of both the solid materials and the lubricant. At one time it was thought that a lubricant would have a constant friction-reducing effect, from the dry state to the lubricated state, i.e. have a certain constant "oiliness" value. This was supported by the idea of an adsorbed film satisfying the surface forces and separating them by an amount proportional to the size and in particular the length of molecule. The position has been shown to be more complicated than that, though the idea of oiliness in this sense should not be lost sight of.

Reference has been made to *solid*, and not just to *metal*, surfaces. This is not only for generality, but because, even in the common cases of metals sliding on each other, the oxide layers that occur on most of them play an important if not a predominant part. There is also some influence due to the worked layer of metal under the oxide layer, formed there by the metal finishing process. Moreover the oxide layer is itself contaminated with gases and moisture from the atmosphere.

Because of the complicated results obtained with ordinarily produced engineering surfaces, and ordinary lubricants, there is a natural trend towards the basic materials of single crystals (e.g. 1) and pure materials as lubricants in fundamental investigations. It will be necessary to consider afterwards the polycrystalline materials, the oxide layers formed on them (including the variations of thickness and possibly crystalline form), the worked polycrystalline materials as produced in machining, the gases and moisture adsorbed on the surface, and the constituents of ordinary lubricants—a formidable programme! It is obviously necessary for engineering purposes to get back to the ordinary surface of practice. It is worth noting that current methods of machining surfaces may not be giving the best type of surface for good rubbing quality, and there is the possibility of far-reaching effects on engineering practice from these fundamental investigations.

BOUNDARY LUBRICANT FILMS

It is appropriate at this stage to describe the behaviour of the lubricant molecules in forming the boundary layer, and the important recent work on the chemical action taking place between fatty acids and reactive metals. Finch is, however, dealing with this part of the subject. His account will form the background for the papers by Shooter, Menter and Moore; for Barwell and Milne in their paper on the lubricating properties of a series of soaps; also for Bielak, Mardles and Tingle's paper dealing with the spreading and lubricating properties of mixed liquids.

EXPLANATIONS OF FRICTION

Friction was in the early days ascribed to the interlocking of surface asperities, and to the work done in sliding one body over another's asperities (the so-called Coulomb friction). More recent work has supported the adhesion theory, by which friction is explained in terms of molecular adhesion between the solid surfaces. With a lubricant present it is adsorbed on or combined with the surfaces, and either reduces or prevents solid-to-solid contact; the adhesion between the lubricant layers is less than between the clean solids, and shear at the interface is easier. It is the covering of a molecular order of thickness in immediate contact with each solid surface which provides the effective lubrication under these boundary conditions; the bulk of lubricant is merely a reservoir from which the surface layers can be renewed if disturbed.

There are still supporters(e.g. 2) for the explanation in terms of roughness alone, but the adhesion theory is widely accepted. As roughness does affect friction, it is a case of modification of the adhesion explanation to allow for any influence of roughness in this physical way; thus Ernst and Merchant(3) include both an adhesion term and a roughness term in their formula relating to cutting tool friction. The effect will only be small unless the roughness is so gross as to be positively serrations interlocking with each other; Strang and Lewis(4) indicate that the mechanical component of friction accounts for only a few per cent of the total friction.

Some of the evidence on adhesion may be mentioned, not merely to show some justification for the theory, but also because of the intrinsic interest. If perfectly clean metal surfaces are brought together they will stick. This is an extreme condition for which it is scarcely fair to talk of a coefficient of friction, but Bowden and Hughes,(5) and more recently Bowden and Young,(6) have shown that the coefficient of friction may be anything from 5 to 100. Fortunately for engineering practice, ordinary metal surfaces are covered with oxide layers and adsorbed moisture and gas films; they all contribute to reducing the adhesion, so that for surfaces in an otherwise meticulously clean condition the coefficients of friction are brought down to a general order of 0·3 to 0·7, depending on the metals in contact. If lubricant is present the coefficient is brought down to an order of 0·1 to 0·3, depending on the type of lubricant as well as the metals.

Tomlinson(7) showed many years ago that a three-legged slider with lead feet would stick to a cleaned glass plate so firmly that the plate could be inverted without the slider falling away. McFarlane and Tabor(8) have recently measured the adhesion between surfaces. If the deformation at the contact is largely elastic the adhesion is not readily shown because the contacting surfaces tend to peel away as the load is taken off. If, however, one of the surfaces is substantially wholly plastically deformed adhesion is readily shown. Moreover, the effect of a lubricant in reducing the adhesion between such surfaces is clearly indicated. These authors have also shown the increase in both friction and adhesion as the tangential load is applied in the early stages leading up to slipping. Parker and Hatch(9) have also reported similar results in another paper containing much valuable information on this part of the subject.

An example of the practical application of the adhesion of metals when clean is provided by the cold-welding of aluminium on a production basis.(10) After rough cleaning the surfaces are squeezed together so as to obtain plastic flow, thus creating surfaces of contact larger than those covered by the original oxide layer; the adhesion occurs between these freshly created clean surfaces and the components are effectively welded together. The importance of the oxide layer, not only in having a much reduced adhesion, but also because of its other properties (strength, brittleness, etc.), is illustrated by this practical case; it has been brought out also in a number of recent investigations.

Of particular importance in the lubrication story is the evidence of metal transfer from a slider to a plate due to this adhesion. Several papers have been published on this subject,(e.g. 11) and there is another one being presented to this Conference by Rabinowicz. Radioactive materials have been a valuable aid in this study. Finch and Spurr also refer to this adhesion in their paper to the Conference.

LAWS OF FRICTION

The generally accepted laws of friction, usually attributed to Coulomb, but discovered earlier by Amontons, are: (1) the friction force is proportional to the load (i.e. the coefficient of friction is independent of the load), and (2) the coefficient of friction is independent of the area of contact. Bowden and Tabor(12) have given an explanation of them in terms of the adhesion theory. They found that the actual contact area between flat surfaces is only a very small fraction of the nominal area; it may be only 1/10 000 of it. The intensity of pressure at the contact points is consequently large even for moderate loads, and plastic flow occurs there. Under these conditions the real contact area (a) increases proportionally to the load W, i.e. $W = af$, where f = flow stress; taking adhesion to occur all over the real contact area, the shear force S to cause movement (= friction force) will increase proportionally to the area a ($S = as$, where s = shear strength of adhesion area), and thus to the load W. It follows, therefore, that the coefficient of friction μ, which is the tangential friction force divided by the normal load, is independent of the normal load; also that the friction force is proportional to the real area of contact, but is independent of the nominal one. Thus

$$\mu = \frac{S}{W} = \frac{as}{af} = \frac{s}{f}$$

This is obviously oversimplified, but has so far been accepted as providing the essential elements of the explanation.

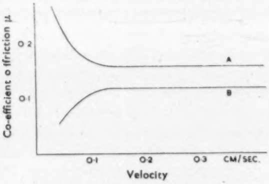
In view of the damage that can occur at solid-to-solid contacts, it is apparent that the shear strength of the adhesion areas can be higher than the shear strength of the surface layers of the weaker of the two rubbing materials, and s then becomes this shear strength. The flow stress f has become a recognized quantity for metals.

Whitehead(13) has recently shown that Amontons' first law holds over an enormous range of loads, even down to extremely low loads of the order of milligrammes. It is not valid, however, for highly finished, geometrically true surfaces, where the real area of contact is much nearer to the nominal area of contact; nor, as Bowden and Tabor(14) have shown, in the particular case of one surface being plated with a thin layer of soft metal. It holds when boundary films of lubricant are present.

In terms of this simple explanation it is possible to suggest a picture of the practical conditions. Although ideally it would seem that, when two surfaces come together under load, the adsorbed or chemisorbed layers would protect the solids from actual contact, the outlying molecules being displaced relatively easily but the more oriented ones taking heavier load, it is now thought that the roughness of surfaces, large compared with even lubricant molecules, leads to local stresses which displace the molecules and give some solid contact. The friction force is thus the sum of the resistance to shear of certain solid-to-solid contacts, drag of primary and other adsorbed films, and viscous resistance of free fluid or semi-solid in pockets. The proportion of each depends on the load, the strength of the adsorption bonds, temperature, etc. The seemingly inevitable variations of friction values in repeat tests would accord with this complexity of the system. The wear and damage to the surfaces which accompany any rubbing under boundary conditions suggest that there is usually some solid-to-solid contact. Although, for example, the transfer of metal from a slider to a plate is much less when lubricated than when dry, it still occurs to a definite extent. Strang and Burwell(15) have shown, using radioactivity methods, that piston ring material is transferred to the cylinder wall during running-in, throughout the whole length of the ring travel, and in a distribution similar to that of the wear which normally occurs in an engine. Rabinowicz is also covering this lubricated condition in his paper, and relates the transfer also to the breakdown temperature noted in other papers.

Variation of boundary friction with velocity. Much of the early work was concerned with the effects of lubricants and other factors on static friction. Most of the recent work has been concerned with the generally more important kinetic conditions, but mention should be made of the paper by Parker, Farnworth and Milne just being issued by the Institution of Mechanical Engineers on the variation of static friction with rate of application of the tangential force. There are particular applications where static friction is important, like the safety clutches mentioned in this paper, switches, and the oil seals of hydraulic rams and jacks referred to other recent papers.(16) Very-low-speed kinetic friction values in many cases differ more from the static values as ordinarily measured than would be expected, and further work is necessary at the very low speeds.

In the kinetic range recent work has shown clearly the effect of sliding velocity on coefficients of friction, and explains some of the anomalies and contradictions of the past. There are two main types of friction/velocity curves, as shown in the accompanying figure [covering a range up to (say) 0·3 cm/sec (0·5 ft/min)]. Type A, with the friction rising with the final decrease of velocity, is the commonest, applying to plain mineral oils and ordinary bearing surfaces. An approximately straight line is obtained on log/log paper. Type B, with the friction falling with the final decrease of velocity, is fairly frequently met; it applies to fatty oils, mineral oils containing a sufficient quantity of fatty oil or fatty acid, etc. A few lubricants show no appreciable change of friction with velocity, but this is probably best regarded as a transition stage from one type to the other. Beyond about 0·1 cm/sec there is usually relatively little change of friction with increase of speed; sometimes there is a slight rise and sometimes a slight fall. Forrester(17) has put forward suggestions as to the combination of factors that might explain the rising and falling characteristics of these curves.



Typical friction/velocity curves

Generally the coefficients of friction are smaller for lubricants giving curves of type B than type A, and such lubricants are therefore better, but there are exceptions, so that it is not always correct to make this deduction.

It should be noted that these curves cover only a range of low speeds. Some work at high speeds has been done in the U.S.A.;(18) friction generally slowly decreases with increase of velocity.

One interesting consequence of the shape of the type A curve, mentioned above, is that if one of the sliding members is elastically mounted it will be made to oscillate by the friction force. These relaxation oscillations are characteristic of a number of sliding contacts; they take practical form in the squeaking and juddering of inadequately lubricated contacts. Viscous damping has sometimes to be heavy to eliminate these vibrations, but when the amount of boundary friction is small, as is usually the case in practical mechanisms, the damping provided by the remaining fluid film is usually sufficient. When the friction/velocity curve is of type B above there is an inherent stability in the friction and oscillations do not occur.

Values for coefficients of friction. The values of coefficients of friction are influenced not only by the natures of the lubricant and rubbing materials, but by the geometrical finish and physical state of the surfaces, as well as by temperature, velocity of sliding, etc. No standard conditions have yet been laid down for the determination. Quoted values are therefore chiefly valuable for comparisons; in the present state of knowledge it is not possible to qualify the values sufficiently, by description of the conditions of measurement, for absolute use.

Although some curious results have been reported, there is as yet no serious disturbance of the traditional general understanding that fatty oils and soaps, and (where tolerable) fatty acids, give lower friction than plain mineral oils, that bearing metals like white metal and phosphor bronze give lower friction with steel than steel on steel, and that grey cast iron is a good bearing material. These points are still the basis for present general lubrication practice as regards friction reduction, and recent research has led to little change being made.

Effect of temperature. In so far as the solids contribute to the friction it has been suggested by Bowden and Tabor,(14) in terms of their formula for coefficient of friction, viz. $\mu =$ shear strength/flow stress, that, as both shear strength and flow stress will be affected by temperature in a similar way, the change in the ratio will be small. On this basis, therefore, the effect of temperature will be associated mainly with the films on the solid surfaces; Finch deals with this aspect in his account of the boundary film and it is also considered in several of the other papers.

Apart from specific effects, such as the melting of the lubricant or the desorption of adsorbed films, the effect of temperature is generally to increase the coefficient of friction, but this is not always true.(e.g. 19) Much work still remains to be done on the friction/velocity curves at various temperatures, and the detailed picture, particularly where chemical action occurs, has still to be worked out. The importance of this work cannot be over-emphasized—most mechanisms work at enhanced temperature and contact temperatures can be very high.

CONTACT TEMPERATURES

It is common knowledge that much heat is developed at rubbing contacts in the absence of lubricant or with an inadequate supply. Some of the contact temperatures found by Bowden and Ridler(20) were, however, a surprise at the time. There has since then been general confirmation of their results. Bowden, Stone and Tudor(21) have demonstrated the high temperatures visually and photographically by using a transparent plate and carrying out the experiments in the dark; they have, moreover, shown the expected effects of speed, load, thermal conductivity, etc. Thomas(22) has used the lead sulphide cell to measure the temperature of the hot spots at such contacts; Parker and Marshall(23) have used the same cell for measuring the surface temperatures of brake drums.

Lane describes results in a paper to this Conference suggesting that for every combination of lubricant and sliding system there is a characteristic temperature at which lubrication fails and seizure of the sliding surfaces occurs.

EFFECT OF ROUGHNESS

Reference has already been made to the estimate that for ordinary grades of finishing the effect of roughness in causing friction due to one surface riding over the roughnesses of the other is small. Roughness may, however, affect the manner in which the surfaces make contact and thus the adhesion between them. Several recent friction investigations have included roughness as a variable, but they do not give a simple picture.(e.g. 24) This is in part due to the effect of roughness of the surfaces not having been disentangled yet from the effect of the physical state of the solid surfaces as modified by the machining process.

One broad trend may be mentioned, viz. that good running is not obtained with very smooth surfaces unless the conditions favour the development of a fluid film. For example, tearing of internal combustion engine piston ring surfaces is liable to occur during running if they and the cylinder surface are initially too smooth. This is probably due to the greater proportion of real area of contact in relation to apparent contact that then obtains. For this reason artificial roughening by etching or mechanical means is sometimes practised, the geometrical truth of the surface being retained. It is thought that the small holes and grooves act as reservoirs for oil, and no point being far from an oil pocket there is less chance of any part of the surface being wiped dry; the larger holes can also serve as a refuge for wear particles. When running-in occurs it often leads to this desirable form of surface with small plateaux and intervening holes and grooves below their level.

ELECTRICAL EFFECTS

Mention should be made of suggestions by Schnurmann(e.g. 25) in particular that electrostatic charges play a part in the rubbing process. He presents a paper on this subject to this Conference.

PRACTICAL IMPLICATIONS

The ideas so far outlined allow the practical behaviour of rubbing surfaces in a number of respects to be understood. Consideration is given below to running-in, wear, scuffing and seizure.

Running-in. With a duty leading to only a thin fluid film carrying the average load in any mechanism, there will be inevitable slight variations of load, vibrations and shocks, etc., which will lead to momentary thinning of the film and contacts of the high points. The contact being brief, and also relatively light, because most of the load will still be taken by the fluid film between the parts of the surfaces not touching, there will be local but not gross generation of heat. At some contacts the generation of heat will be so little that the adsorbed film will not be dispersed by thermal agitation of the molecules and the shearing action will not be great enough to remove it. At others, however, there will be local solid-to-solid adhesions within the tiny contact areas, and there will be greater stress on the solids, together with rise of temperature. The strength of the bond may lead to shearing occurring within the softer solid and some of it being taken away on the mating surface; sometimes particles of the harder solid will be removed, due to local weakness present initially or induced by repeated stressing in successive rubbing contacts. At yet other contacts there will be interlocking of roughnesses of the surfaces and a consequent removal of metal by shearing (like filing on a very small scale). There will be some adhesion of the detached particles to the mating surface, but others will be permanently detached and remain in the oil. The detached particles are bits of the oxide layers, sometimes with metal attached, and their permanent removal constitutes wear. At the same time as the removal of the particles from high spots, there will usually also be some plastic flow due to the normal and tangential forces.

As up to this stage these contacts are considered to be brief and relatively light, the heat developed, though at some contacts sufficient to be significant, is not great in the aggregate. It will be dispersed through the metal and taken up by the oil without serious reduction of the general viscosity; the load carrying capacity of the fluid film will therefore not be significantly reduced. Moreover, the particle removal will be from the high points of the surfaces and the geometric mating of the surfaces will be improved, the film space being made more uniform; the ability to take additional load, steady or shock, without contact will therefore be greater. The system is thus inherently stable, and the process of improvement of the surfaces in this way constitutes basically "running-in," so much discussed in connexion with the initial use of mechanisms.

It is interesting to note that Bezer and Schnurmann,(26) and also Whittaker,(27) have worked out that the energy used in detaching wear particles is very small compared with that used in friction.

Wear. The release of particles from surfaces by occasional contacts severe enough to break through the boundary films has been pictured above. This is one stage of wear. These particles, together with others from the exterior of the system, e.g. airborne dust, will get trapped between the surfaces, particularly frequently where the film is thinner due to high spots. They will consequently sometimes be broken down to smaller sizes. On the other hand they will often damage the rubbing surfaces by local penetration and crushing of the solid, or by scratching, so that material is sometimes removed directly to make more circulating particles or is "ploughed up" and damaged to provide further particles when other adhesions occur. Sometimes the particles will be embedded in the softer rubbing material and will leave prominent cutting points to scratch the mating surface. There will be momentary increases of friction, but little steady rise, as these contacts are made.

It is apparent that these particles circulating with the oil can cause wear of the surfaces even when the fluid film is thick enough to carry the load without contact of the bearing surfaces occurring. Filters, and quiescent periods for the oil in its circulation to allow settling, will help to remove the larger particles, but there is evidently a limit to the efficiency of particle removal. Wear seems to occur with any running mechanism, and it appears that the most that can be done is, by design and filtration, to keep the wear within the tolerable economic limits.

Many attempts have been made to measure wear in the laboratory, and in particular to establish the comparable wearing characteristics of materials. It is not difficult to see from the complexity of the contacts of surfaces why an enormous amount of work (as shown by the literature) has led to so little practical result. There has been some benefit, particularly where the test conditions have imitated the practical case and where some particular feature has been investigated. Much more work of an exploratory kind is necessary, and encouragement should be given to the building up of a clear understanding of the wear process. The ultimate reward will be great. In the meantime for the practical man the rules are to design if possible for a fluid film, to keep the lubricant clean, and to use lubricants that have protective value for the surfaces (they are usually the same for friction reduction as for wear reduction, though these are not proportionally connected and in odd cases may have opposite trends(28)). In particular cases use can be made of specific anti-wear additives.

Grodzinski's paper describes the removal of material by grinding and lapping. The mechanisms of the processes are similar to those of wear, but in his case the removal is deliberately fostered.

A little more may perhaps be said about the anti-wear additives. Tricresyl phosphate appears to have come into increasing use for this purpose, and iron carbonyl has been added to internal combustion engine oils. Beeck, Givens and Williams(29) have suggested that the phosphorus-containing materials function by the formation of iron phosphide at high temperature at high points of contact, the iron phosphide forming a eutectic with iron of lower melting-point than iron, and flow then relieving local pressure without loss of material; there is thus promotion of fluid film lubrication. They also showed that there was a further reduction of wear when an adsorbable polar lubricant was present. The theory was checked by the prediction and verification of equally good results from arsenic-containing additives in the oil, and absence of advantage with tin-containing rubbing materials like bronze. Clayton and Jenkins include in their paper a few results relating to these anti-wear additives.

Whilst a wear-reducing agent may sometimes be desirable in the long-term running of a mechanism, it is important to recognize that the prior use of a wear-promotion agent might be desirable in some cases to secure quick running-in of a mechanism, e.g. in gears, and in internal combustion engine cylinders to obtain a stable oil consumption and gas tightness quickly. Extreme pressure lubricants have been used in this way for gears.

Scratching and scoring. Scratching of the surfaces has been referred to above as a consequence of particles getting trapped between the surfaces. When the scratch is deep it becomes difficult to distinguish from a score due to severe local adhesion, such as marks the early stages of scuffing described below; it is best to keep the term "scoring" for the latter phenomenon.

Scuffing and seizure. Taking the regime described under "running-in" and considering further increase of duty, in particular of load, it is evident that with the decrease of fluid film thickness, the frequency of high point contact will be greater and more of the load will be taken by the solid surfaces during each of these periods. The heat developed will be greater, leading firstly to a disorientation of boundary films, so that their protection is less; secondly, to higher local temperatures, increasing the area of the adhesions; thirdly, to lowering of the viscosity of the oil, so that the load it can carry hydrodynamically in between the contact areas becomes less and more is left to the solid contacts, and so on. It is evident, therefore, that with increase of duty the system can become unstable, each factor worsening the others. The adhesions become more extensive, and the effect on the solid surfaces more deep-seated. Larger portions of oxide and metal are torn from their parent bodies, so that the surfaces become rougher instead of smoother, and the torn-out material becoming jammed between the surfaces causes further damage.

This tearing of the surfaces is called "scuffing." If the load causing scuffing is temporary, and in just a few other cases, recovery to a stable condition is possible, but generally the conditions worsen, and so much adhesion develops that the driving force is exceeded and the mechanism stalls. This is what is understood as "seizure."

Clayton and Jenkins' paper deals mainly with a particular aspect arising from scuffing or approach to it, viz. a physical transformation of the material in the rubbing surfaces (cast iron and hard steel) due to the high temperatures reached superficially and to the rapid cooling due to contact of the thin top layers with cooler bulk material.

EXTREME PRESSURE LUBRICANTS

The need for extreme pressure lubricants has arisen with the hypoid back-axle gear, in which there is a high intensity of contact pressure and a higher relative speed of sliding than usually obtains in gears. There has been much investigation of these severe conditions and large numbers of additives have been tried, chiefly those containing sulphur and chlorine. So far as the practical application of extreme pressure lubricants goes, however, the position seems to be fairly well stabilized: satisfactory commercial grades are available to meet the existing needs. Moreover, where the conditions are not as severe as in a hypoid gear, there are compositions suitable for these milder conditions. There has, therefore, ceased to be an urgency from the practical point of view in the investigation of extreme pressure lubricants.

There is still considerable interest, however, in the academic aspect of the way these materials function. Broadly they are thought to react with the metals or their oxides at the high rubbing temperatures to form easily sheared and anti-adhesion layers of iron sulphide or chloride. But Finch and Spurr deal more fully with this subject.

SOLID LUBRICANTS

For some applications solid materials are useful for lubricating purposes. Graphite has been so used for many years, both dry and incorporated in lubricant as a colloidal dispersion. Its value has been commonly explained on the basis of its plate-like crystal form, providing easy shear, and coating the contact surfaces with a layer protecting them from adhesion. Reference should, however, be made to the work of Savage(30) showing the importance of moisture in its action, and at right angles to the direction of rubbing. Campbell and Kozak(31) do not agree with the moisture suggestion. Recently much attention has been drawn to molybdenum disulphide as an alternative solid lubricant, with a slightly different explanation.(e.g. 32) Barwell and Milne give a paper on the behaviour of some solid lubricants.

SURFACE TREATMENTS AS AN AID TO LUBRICATION

Thin coatings of soft metal on a hard substrate have been used to promote good boundary behaviour of rubbing surfaces. Friction reduction to $\mu = 0{\cdot}04$ has been shown for an indium film on steel with a steel slider, without lubricant.(14) It is thought that one essential feature of copper-lead bearings is that the lead smears as a thin film over the harder copper.(33) Tin has been used on pistons to prevent piston and ring scuffing in internal combustion engines(e.g. 34); it has been suggested that the tin gradually gets transferred to the cylinder walls and so assists at the contact with the rings, filling in roughnesses and promoting fluid film formation, and probably providing at high points a relatively easily sheared inter-layer.

Chemical pre-treatment of surfaces also offers a potentially useful alternative to adding materials to the oil.(35) A sulphide or oxide layer may be provided which will allow easy running-in and act as an anti-adhesion layer under severe conditions; such a procedure has the advantage of allowing chemical substances to be used which might be objectionable when distributed in the oil, but on the other hand, the surface is not renewable in service. Of particular value from this point of view, and much better known than the other processes, is phosphating,(e.g. 36) by which a layer (0·0003 to 0·0005 in) of mixed iron and manganese (or zinc) phosphates is formed at the surface. The layer is relatively friable and therefore facilitates running-in; moreover, it is thick enough to make high finish (which is expensive) unnecessary. When the main layer has been worn away, the surface is slightly pitted, and thus favourable to lubrication (as has previously been mentioned). Under severe conditions the layer plays an anti-scuffing role, as though having extreme pressure properties; thus the load-carrying capacity of spur gears with a mineral oil can be doubled by phosphating.(37) It also acts as an anti-adhesion layer, as in the prevention of scuffing of piston rings in cylinders under certain conditions. Barwell and Milne deal with phosphating at some length, and Clayton and Jenkins give a few good results for it in their paper.

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DISCUSSION

Dr. F. T. Barwell: Dr. Clayton's comprehensive review indicates the complexity of the subject and shows the need for caution in applying the results of specific experimental work to practical cases where different conditions may be expected. Generally we can define friction as the tangential reaction between two solids in relative motion subject to a normal force. It is not surprising that it is generally found that the reaction is proportional to that normal force and indeed the coefficient of friction might better be described as the partial regression coefficient connecting load with tangential force. To confine, as some physicists do, the definition of friction to those circumstances in which Amontons' law is obeyed, is to evade the responsibility for providing the mechanical engineer with a great deal of data of which he at present stands in need. Further, the search for some single principle which will explain friction and which ascribes Amontons' law to some unique mechanism is unlikely to be successful and advance in the subject can only be expected as a result of experimentation wherein the influence of many factors can be isolated. Indeed, lubrication under boundary conditions, where results are conditioned by such factors as hardness, roughness and chemical nature of surfaces, is likely to be governed by more than one physical principle and a sound factorial design is necessary if we are to be sure of the range of application of any results obtained.

Dr. Clayton spoke of hydrodynamic lubrication and boundary lubrication, mentioning that in many practical cases there might be mixed conditions. I am not sure that there may not be a clearly defined intermediate region which is neither hydrodynamic in the Reynolds sense nor boundary lubrication, and would prefer the use of the term "thin film lubrication." It is possible that some lubricants are effective by reason of their bulk rheological properties more than by purely surface effects, and it is to be hoped that discussion in the conference will reveal an interest on the part of the rheologist in some of these difficult questions.

Dr. Clayton mentioned that characteristic friction-velocity curves might be either horizontal, falling or rising, and I wish to put forward the following hypothesis as a basis for discussion. The rising characteristic, which was found with good lubricants, might be indicative of the complete separation of the two surfaces by material which was sufficiently strong to withstand normal forces in compression. As the rate of shear of this lubricant increased so would the coefficient of friction, but if the material were a Bingham solid the coefficient of friction at zero velocity would be conditioned to some low value by the yield value. The falling characteristic might be indicative of imperfect lubrication permitting intermittent contact and shearing of the metallic surface at a number of points dependent on its efficiency. It was possible to infer from results on the forces required to machine metals that the slower the shearing was done the higher was the resisting force. It might therefore be that the falling curve arose from the rheological character of material of the sliding surfaces and that it was revealed to a greater or lesser degree by the efficiency or otherwise of the boundary lubricant in separating them.

Dr. H. Blok: In the paper attention is justly drawn to the fact that above all in hypoid gears extreme pressure lubricants are a *conditio sine qua non* for avoiding scuffing of the gear teeth. Now it seems that there is still a widespread opinion that the distinctive thing about hypoid gears would be that contact pressures between the mating gear teeth would be significantly higher than those in other kinds of gears, and that this would constitute the basic cause of the distinct need for extreme pressure lubricants in the hypoid gears. This is not so, however: in effect it is not the contact pressures, but the contact temperatures which are critical as to scuffing of gear teeth and it is these contact temperatures that are bound to become much higher in hypoid gears than they do, for instance, in spiral bevel gears with similar contact pressures. This feature is due to the fact that in hypoid gears, apart from the kind of relative tooth motion that also prevails in spiral bevel gears, there is an additional sliding motion that takes place in the longitudinal direction of the band-shaped contact surfaces; the result is that any given point on a tooth face of a hypoid gear is exposed during a comparatively long time to the frictional heat which is developed in the contact surface, so that contact temperatures become appreciably higher than those in spiral bevel gears. In fact, the term "extreme pressure lubricants" is a misnomer; however, it would be hard to introduce a new term to supersede the present one, as it has already been generally adopted in commerce.

Dr. E. D. Tingle: Dr. Clayton has reported that Whitehead has found that Amontons' law of friction is obeyed over a wide range of loads. This is true for two of the three metals that Whitehead used in his pioneering work at light loads. He found that the coefficient of friction for a hemispherical slider of aluminium sliding on an aluminium plate remained constant when the load on the slider was changed from a few milligrammes to several kilogrammes. The same was true of silver. Copper, however, was an exception to this behaviour. The coefficient of friction was one constant at higher load, passed through a period of fluctuation as the load changed from 10 to 1 g and then assumed another lower constant value for loads down to a few milligrammes. Whitehead connects this behaviour, on evidence obtained from electron microscopy, with the presence of a protective oxide layer on copper which is dented, but not pierced in the lower load range. It is interesting to note that Krotov and Khachadurova* arrive at very similar conclusions in an investigation of the effect of load on the depth of scratch of a steel needle on an aluminium surface.

Whitehead's results have significance not only for the dry friction of metals but probably also for their boundary lubrication. It is possible that the boundary regime of lubrication may be divided into two or more regions depending upon the layer structure of the sliding surfaces and the load between them.

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* KROTOV and KHACHADUROVA. *Bull. Acad. Sci., U.R.S.S.*, p. 50 (1948).

The boundary layer

By Prof. G. I. Finch, M.B.E., D.Sc., F.Inst.P., F.R.S., Imperial College of Science and Technology, London

The author reviews the present state of knowledge of the liquid and solid lubricant boundary layer. The function of the boundary layer is to replace the oxide-layer component of friction by one of still lower value. The structure of the oil boundary layer is discussed, and the effects of heat and sliding on this structure, particularly on the orientation of the lubricant molecules. Solid lubricants of the layer lattice type depend for their functioning on a large ratio of surface area to particle mass, and having on their surfaces firmly adhering liquid or gaseous adsorbed layers.

The function of the oxide layer is to prevent intermetallic friction with its more or less destructive consequences. The oxide- (or sulphide-, etc.) layer component of friction, however, is still too high to be tolerated in general sliding practice, even supposing the layers could remain intact. It is the function of the boundary layers of the lubricant to replace the oxide-layer component of friction by one of still lower value.

The lubricants consist, in general, of mixtures of straight-chain hydrocarbon molecules (paraffins) or their end-substituted products (alcohols, esters, ketones, acids). At temperatures below the melting point of the hydrocarbons, the chains, 4·5 A apart, are grouped in bundles, like sticks in fascines. Such bundles are, in fact, crystals. When grown from the melt or solution on a solid surface the crystals are orientated with the chains either vertical or inclined to the surface at an angle characteristic of the compound.(1) The thickness of such an orientated crystalline layer may be as much as 50 molecules or more.

When such layers are heated, as they are under practical conditions of sliding, the fascines break up at a temperature close to the melting point, leaving a true boundary layer of molecules. The molecules attached directly to the surface are normal or steeply inclined to it; above them is a layer of less pronounced orientation, and by the time the fourth layer is reached the orientation is practically non-existent; that is to say, the film has now become fluid.(2) The maximum thickness of the boundary layer is therefore of the order of less than 200 A.

The chains of the first layer in the boundary film are all adsorbed with one end attached to the oxide film, the radicle end in the case of end-substituted molecules. Owing to the polar nature of these, they are more firmly held than the normal paraffins. Further, acids or esters may react with the oxide, sulphide or other layer to form soaps; in this case the relatively thick crystalline soap layer persists up to its softening temperature.(1,3)

The transition from a crystalline to a boundary film is reversible in that, on cooling, the crystals are re-formed.(1) In consequence, new orientations of the crystals or fascines are observed after rubbing. For example, solidified fatty acid films are frequently found to contain crystals in which the molecules are alined in the direction of sliding at an angle of about 5° to the surface.(4,5)

Boundary-layer friction is lower with end-substituted than with normal paraffins of similar chain lengths.(6) This has generally been attributed to their stronger adhesion to the oxide layer. It is difficult, however, to see how this can materially reduce friction. It may be said, indeed, that present views on the mechanism of the facilitating of sliding by the lubricant boundary layer are inadequate. It is true that I have at times likened the boundary layer to a velvet pile or the bristles of a brush, and have also drawn attention to the thermal motion of the molecules of the layer and to possible effects of their polarity. But all these ideas are at best working hypotheses meant only to serve as guides to further experimental inquiry.

Many lubricants also contain, or may even consist largely of, cyclic compounds. Their modes of orientation, when adsorbed as surface boundary layers, have so far not been systematically studied. Anthracene crystals deposited on a stainless steel surface by evaporation from an ether solution are in (001) orientation. The anthracene molecules, therefore, lie with their longer axes at about 60° to the surface. Rubbing of such a deposit results in an anthracene layer the reflexion pattern of which reveals, irrespective of the beam azimuthal direction, only those diffractions which lie on the vertical central, i.e. [001], row.(7)

Boundary layers are also formed by solid lubricants. These are generally layer-lattice structures, such as micas, clays, graphite and molybdenite, the flakes of which become adsorbed on the sliding surfaces. It is commonly supposed that the layer-lattice crystals act like orientated packs of playing cards. This view is misleading and is negatived by the fact that the layers of layer-lattice crystals can be separated only by cleaving in such a manner that the bonds between the layers are broken one by one. Surfaces, freshly exposed by cleavage in air, will cohere firmly on being put together again, and cannot be pulled apart by a stress applied in a direction lying in the cleavage plane (i.e. by attempting to rupture the bonds simultaneously). They lose this property, however, on prolonged exposure to air or on brief immersion in water or a liquid lubricant. Thus the ability of layer-lattice cleavage surfaces to slide easily over each other is due to adsorbed layers. Layer-lattice crystals with their *c*-axes parallel to, and crushed between, loaded sliding surfaces will be cleaved, but will also abrade the sliding surfaces. It follows that layer-lattice crystals in which the ratio of exposed cleavage plane area to thickness in the *c*-direction is a maximum make the best form of solid lubricant. It is known from electron diffraction and electron-microscopic studies[8] that the smaller the volume of a graphite crystal the higher is the value of the above ratio. A layer-lattice lubricant should, therefore, consist of crystals in the finest possible state of subdivision compatible with a maximum surface to thickness ratio. Sliding of the lubricated mechanism should not be relied on to break up the crystals, as this must result in wear.

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Scuffing temperatures of boundary lubricant films

By T. B. LANE, M.Sc., A.Inst.P., Shell Refining and Marketing Co. Ltd., Thornton Research Centre, Chester

The postulate of Blok that lubrication will fail when the temperature in the contact area reaches a value characteristic of the lubricant and sliding system is confirmed by experiments on the two-ball machine. It is shown that for the range of mineral oils tested the failure temperature increases with viscosity.

In the region of hydrodynamic lubrication, viscosity will determine the relative performance of oils as regards their load-carrying capacities in any given mechanical system. When lubrication is by boundary film no such simple parameter exists and comparisons can only be made in some other way, for example in terms of failure load on a suitable test machine. Such methods are useful but have their limitations especially when attempts are made to translate results obtained on one machine to performance predictions in another application. A possible way of overcoming this difficulty is afforded by the postulate of Blok[1] that for every combination of lubricant and sliding system a characteristic local temperature exists at the surface of contact at which lubrication fails and scuffing occurs—at least in gears and in test machines using steel test pieces. This temperature for failure will then be the measure of the lubricating ability of the oil. This contribution deals with the examination of an expression based on this concept relating the operating variables of a test machine.

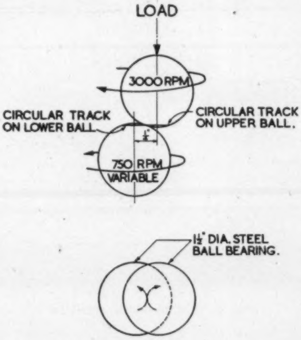
LOAD
3000 RPM
CIRCULAR TRACK ON LOWER BALL
CIRCULAR TRACK ON UPPER BALL.
¼"
750 RPM VARIABLE
1½" DIA. STEEL BALL BEARING.

Fig. 1. Principle of two-ball machine. Motion at point of contact is combined rolling and sliding as in gear tooth engagement. Severe loads cause surface breakdown.

APPARATUS

The apparatus employed was the two-ball machine, the idea of which originated with Dr. H. E. Merritt. The machine was supplied as a prototype by David Brown & Sons (Huddersfield) Ltd., but has subsequently been considerably developed for research purposes at the Thornton Research Centre. The principle is illustrated in Fig. 1. The two steel balls of 1½ in diameter are mounted at the respective ends of two vertical spindles, the axes of which are ¼ in apart. Both spindles are capable of rotation, in the same or opposite direction as required and also at different speeds. Conditions of combined sliding and rolling in the contact are thus produced. Fig. 2 shows the apparatus. It consists essentially of two parts, coupled by a horizontal hinge so that the upper part can be tilted back clear of the lower. Each part carries a spindle, hollow at one end, into which the test pieces are secured by means of special chucks.

When the two halves are closed together the two balls are brought into contact and the load between them can be varied by means of weights on the loading lever. The balls are, however, kept out of contact until the experiment is ready to commence by means of the hand-operated cam. The test lubricant is carried in a circular dish mounted coaxially on the lower chuck. Rotation causes the oil to be flung outwards against the vertical walls of the dish and to form a layer in which two scoops are immersed so as to deflect two jets of oil on to the lower ball. Temperature control of the lubricant under test is provided by means of an annular electric heater within which the oil dish revolves, temperatures are measured at convenient intervals by placing a mercury thermometer in the oil stream.

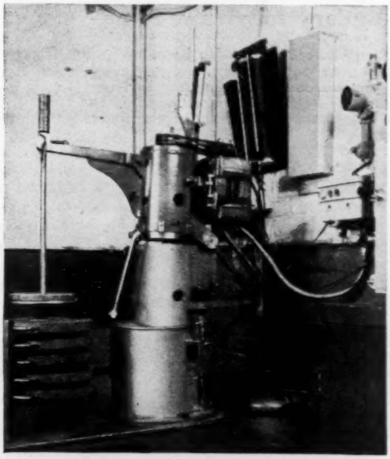

Fig. 2. The two-ball machine

A test on a lubricant is carried out by bringing the balls, already rotating, into contact under the appropriate load and allowing them to run together until failure occurs or until a period of fifty seconds has elapsed, whichever is the earlier, as experience has shown that failure is unlikely to occur after fifty seconds. Failure, the cause of which is the same as the cause of scuffing in gears, is indicated audibly and results in severe surface damage. A successful run, during which no lubrication failure has occurred, affects the surface very little, at least visually, merely producing a polished track which is sometimes coloured black or brown, depending on the nature of the lubricant employed. When the load has been carried successfully the balls are turned within the chucks to bring fresh surfaces into contact and the process repeated with a loading on the balls ten pounds greater than previously; this is continued until failure occurs. As a rule five such determinations are made on each oil and repeatability is found to be good.

THEORY

List of Symbols

θ_0 = initial temperature of test pieces in °C.
$\Delta\theta_F$ = maximum value of the temperature-flash in the contact area in °C.
$\Delta\theta_s$ = surface temperature-rise of track in °C.
θ_c = temperature for failure in °C.
v_1 = velocity of path of contact on the upper ball in cm/sec.
v_2 = velocity of path of contact on the lower ball in cm/sec.
r = radius of the deformation area produced by the load in cm.
W = applied load in grams.
W_F = failure load in grams.
μ = coefficient of sliding friction in the contact.
ρ = density in g/c.c.
c = thermal capacity in cal. g^{-1} °C^{-1}.
k = heat conductivity in cal. sec^{-1} cm^{-2} °C^{-1} cm.
R = relative radius of curvature of the balls in contact in cm.
Q = total strength of heat source, cal./sec.
q = intensity of heat source, cal. sec^{-1} cm^{-2}.
α = $\Delta\theta_s/\Delta\theta_F$; a numerical constant depending on load and speed.

The frictional heat developed in a sliding contact produces at each point on the surface a rise in temperature of short duration which has been called the "temperature-flash" for this reason. The magnitude of this temperature-flash $\Delta\theta_F$ will be constant for given conditions of load, speed and coefficient of friction and after the passage of the heat source, the temperature of the surface if infinite in extent will soon return to its original value as the frictional heat is dissipated. On the two-ball machine, however, a point on the path of contact will be subjected to repeated applications of frictional heat in rapid succession, so that the surface temperature will not have fallen to its original value after the liberation of one increment of heat before the arrival of the next. Thus the temperature of the surface for given conditions will gradually rise by an amount $\Delta\theta_s$ due to the accumulation of frictional heat until it reaches equilibrium. Thus the temperature θ in the contact area will gradually rise to a value

$$\theta = \theta_0 + \Delta\theta_s + \Delta\theta_F \qquad (1)$$

Blok⁽²⁾ has obtained an expression for the temperature-flash occurring on gear teeth by considering them as parts of rotating cylinders. This expression may easily be adapted for the contact between steel spheres and leads to

$$\Delta\theta_F = 1{\cdot}48\frac{\mu(v_1 - v_2)\sqrt{W}}{(\sqrt{v_1} + \sqrt{v_2})\sqrt{R}} \tag{2}$$

provided that v_1 and v_2 are both greater than 20 $k/\rho cr$. This is true for the upper ball but not for the lower, but inspection of the curves given by Jaeger⁽³⁾ for the distribution of temperature within the contact show that the error is unlikely to be large.

The form of expression for $\Delta\theta_s$ may be obtained by considering the area contact as a stationary heat source. Blok⁽⁴⁾ and Jaeger⁽³⁾ have shown that the maximum temperature at the centre of such an area is qr/k and since in this case $q = Q/2r\pi d$, where d is the diameter of the path of contact, $\Delta\theta_s$ depends on the product $W(v_1 - v_2)$. Thus $\alpha = \Delta\theta_s/\Delta\theta_F$ will not be constant and will vary as $(\sqrt{v_1} + \sqrt{v_2})\sqrt{W}$ but although this variation is $\pm 30\%$ of its mean value within the range of these experiments, it may be regarded as approximately constant since the effect of α itself on the contact temperature is small.

Lubrication failure will occur when the failure temperature θ_c for the lubricant and sliding system is reached. Then

$$\theta_c = \theta_0 + (1 + \alpha)1{\cdot}48\frac{\mu(v_1 - v_2)\sqrt{W_F}}{(\sqrt{v_1} + \sqrt{v_2})\sqrt{R}} \tag{3}$$

The value of α may be evaluated experimentally by observing the failure load for a test of short duration (when $\Delta\theta_s = 0$) on the one hand and the failure load under equilibrium conditions on the other.

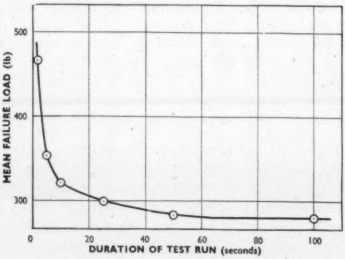

Fig. 3. Variation of failure load with duration of run. Sliding velocity 172 ft/min. Oil temperature 60° C, oil viscosity 15 cS at 60° C.

This aspect is illustrated in Fig. 3 and it is seen that for a test of short duration $W_F = 500$ lb approximately, and when $\Delta\theta_s$ has attained its equilibrium value $W_F = 280$ lb. Therefore $\alpha = \sqrt{(500/280)} - 1 = 0{\cdot}34$. Substituting this value for α in equation (2) leads to

$$\theta_c = \theta_0 + 1{\cdot}99\frac{\mu(v_1 - v_2)\sqrt{W_F}}{(\sqrt{v_1} + \sqrt{v_2})\sqrt{R}} \tag{4}$$

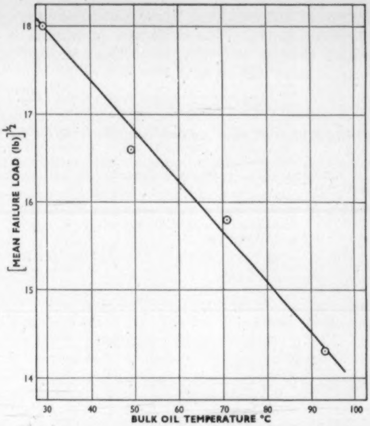

Fig. 4. Variation of failure load with bulk oil temperature. Sliding velocity 172 ft/min. Duration of run 50 sec. Oil viscosity 15 cS at 60° C.

EXPERIMENTAL

The validity of equation (4) with respect to temperature, surface speeds and ball size was then investigated, using, so far, mineral oils only. Fig. 4 shows the effect of operating oil temperature. Fig. 5 shows the effect of ball speed and the table shows the effect of relative radius of curvature for pairs of balls of 1 in and 1½ in diameter respectively.

Effect of relative radius of curvature on failure load

Sliding velocity: 172 ft/min (77 cm/sec)
Oil temperature: 60° C.

Oil viscosity cS at 60° C	*Failure load (lb)*		*Ratio*
	1½ in balls	*1 in balls*	
8	250	170	1·47
15	275	202	1·36
34	346	230	1·50
81	383	238	1·60
148	418	280	1·49

DISCUSSION

In basing this work on the two-ball machine, the assumption has been made that no hydrodynamic film can exist in the contact and that lubrication is wholly by boundary film. Support for this view is given by Howlett⁽⁵⁾ who showed that such was the case for the four-ball machine except at loads of 50 g or less. Adapting his expression for the two-ball machine leads to similar conclusions that the loads employed in the present work are greatly in excess of those capable of support by a hydrodynamic film. The magnitude of the coefficient of friction also indicates that conditions are of a boundary nature. The coefficient of friction is not measured directly but may be deduced from Fig. 4. The equation of this curve is

$$340 = \theta_0 + 0 \cdot 81 \sqrt{W} \qquad (5)$$

and comparing this equation with equation (4) we see that

$$0 \cdot 81 = 1 \cdot 99 \frac{\mu(v_1 - v_2)}{(\sqrt{v_1} + \sqrt{v_2})\sqrt{R}}$$

whence $\mu = 0 \cdot 07$

since $v_1 = 114$ cm/sec
$v_2 = 26 \cdot 9$ cm/sec
$R = 0 \cdot 95$ cm

in this case.

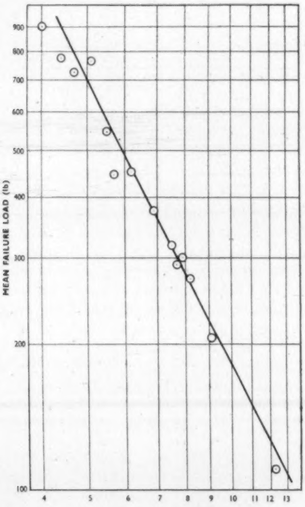

Fig. 5. Variation of failure load with rolling and sliding velocity. Duration of run 50 sec, oil temperature about 30° C, oil viscosity 15 cS at 60° C.

It would appear then that lubrication is largely boundary in these experiments and the data obtained confirm the truth of equation (4). In Fig. 5 the slope of the curve is $-1 \cdot 9$ agreeing well with the theoretical value $-2 \cdot 0$. The table shows that the effect of change in R is as expected; the theoretical value of $1 \cdot 5$ for the ratio of the loads in the two cases is approximately obtained for all oils.

Thus it appears that the original postulate of a characteristic temperature for failure is a correct one. Equation (5) indicates that failure possibly occurs in the region of 340° C for the oil in question and the table shows that the failure temperature is probably different for different oils and this was confirmed by experiments in which the oil temperature was varied as in the experiment described in Fig. 4, the oil of 148 cS for example having a failure temperature of roughly 500° C.

CONCLUSIONS

It appears that the idea of a temperature for failure can account satisfactorily for the behaviour of boundary films in the present instance and that such a concept will greatly assist in the development of test methods, as it has in fact already done (e.g. for the four-ball machine and the seizure-delay method(1)) and will lead to a better understanding of lubrication under these conditions.

ACKNOWLEDGMENTS

I express my thanks to the Shell Refining and Marketing Company Ltd. for permission to present this paper and to make use of the test data; also to friends and colleagues at Thornton Research Centre, who participated in some of the work described or for helpful criticism.

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Lubrication with materials in the solid state

By F. T. Barwell, Ph.D., M.I.Mech.E., and A. A. Milne, B.A., Lubrication Division, Mechanical Engineering Research Organization, Department of Scientific and Industrial Research, Thortonhall, Nr. Glasgow

Coefficients of friction between flat mild steel surfaces loaded at an average intensity of 40 lb/in^2 at relative velocities of 0·01 cm/sec and 0·4 cm/sec were determined using talc, vermiculite, flake graphite, paraffin wax and various metallic soaps as lubricants. Only graphite, the metallic soaps and paraffin wax were shown to be effective lubricants and paraffin wax was selected for further study under conditions more in conformity with engineering practice. Results are given of tests in which mild steel treated by tin plating, chromium plating and phosphating was continuously reciprocated against mild steel both unlubricated and lubricated with paraffin wax. A phosphated surface, lubricated with paraffin wax, formed the most satisfactory combination and it is suggested that, under the conditions embraced by the experiments, the porous nature of the surface coupled with the rheological properties of the paraffin wax might be the determining factors in performance.

Conditions sometimes arise in practice where it is undesirable to use a liquid lubricant but where some protection against wear and seizure is imperative. Powders are sometimes employed for this purpose, and it is of interest to compare their effectiveness as lubricants under conditions which are clearly not hydrodynamic and yet which do not appear to permit the intimate association of rubbing surfaces characteristic of boundary lubrication.

The experiments described were carried out with a particular industrial application in mind and the range of variables was therefore restricted. As a first approach measurements were made of the kinetic boundary friction of a series of substances and the most promising was selected for more detailed study, particular attention being given to the ability of the treatment to withstand continuous rubbing without replenishment.

MEASUREMENTS OF KINETIC BOUNDARY FRICTION

Table 1 gives the results of friction determinations using some of the conventional solid lubricants between two surfaces of mild steel. The measurements were made using the N.P.L. kinetic boundary friction machine,$^{(1)}$ but the upper surface consisted of a circular flat having an area of 0·05 in^2, giving a nominal pressure between the surface of 40 lb/in^2. It is to be noted that the nominal pressure used is considerably below that normally used in kinetic friction experiments, and although the results are quoted as coefficients of friction this does not imply that Amontons' law holds under these conditions. The lower surface was cleaned by scrubbing with caustic soda solution until, on washing with water, the surface was entirely wetted.

In each case the upper surface was polished by reciprocating the lower carriage of the machine, which was covered with emery paper. This method of finishing ensured parallelism between the upper and lower friction surfaces.

Table 1. *Coefficient of friction for various substances between mild steel and mild steel (finished by machine grinding to an average reading of 5 μin)*

	Coefficient of friction	
Substance	*Speed, 0·01 cm/sec (0·24 ft/min)*	*Speed, 0·4 cm/sec (9·45 ft/min)*
Talc	0·5	0·63
Vermiculite	0·48	0·42
Bentonite	0·37	0·45
Micaceous iron ore	0·38	0·36
Camphor	0·35	0·33
Aluminium stearate	0·3	0·4
Mica (muscovite)	0·28	0·48
Stearic acid	0·15	0·19
Copper stearate	0·10	0·12
Flake graphite	0·11	0·12
Paraffin wax	0·10	0·13
Zinc stearate	0·09	0·09
Sodium stearate	0·08	0·08

Talc, hydrous magnesium silicate, $Mg_3Si_4O_{10}(OH)_2$, often found in association with hydrous aluminium silicate, $Al_2Si_4O_{10}(OH)_2$, is one of the softest minerals known. Nevertheless, its position at the head of the table indicates that softness has little to do with lubrication.

Mica, which can exist in at least three mineral forms, is characterized by a laminar structure so that, when ground, it forms thin plate-like particles not dissimilar to flake graphite. The three principal varieties of mica are white mica or muscovite, a hydrated silicate of aluminium and potassium, amber mica or phlogopite, and black mica known as biotite. Muscovite was selected for test as it is the most common form in industrial use.

Vermiculite is a form of biotite which has been subjected to certain geological conditions which leave the mineral in such a condition that, when heated, the laminae separate so that the material appears to expand laterally from 10 to 500 times.

Vermiculite is second on the table and mica gives comparatively high friction. The results therefore throw doubt on the view that a laminar structure necessarily endows a substance with lubricating properties.

The graphite used was commercial flake graphite, consisting mainly of flakes about 0·01 mm^2 and having an ash content of 0·47%.

The metallic soaps were prepared by the Chemical

Research Laboratory, Teddington. The paraffin wax was of B.P. quality and had a melting point of 55° C.

It will be noted that only metallic soaps, graphite and paraffin wax can be regarded as satisfactory lubricants.

EXPERIMENTS UNDER CONTINUOUS RUNNING CONDITIONS

Method of test.—Paraffin wax was selected for further study and tests were carried out under continuous running conditions, using the reciprocating machine, described elsewhere.(2) The conditions of test were selected to accord with those likely to be encountered in mechanisms lubricated under boundary conditions. The nominal load was 5 lb acting on a test piece (6·7 lb/in^2), but in cases where a test lasted 50 h without failure, load was increased up to 200 lb by increments of 5 lb at 2 min intervals. A continuous indication of friction force was obtained by restraining the upper specimen in a block, by strips to which resistance strain gauges were attached, changes in resistance being registered on a cathode-ray oscilloscope.(2) The lower test piece was held in the oscillating carriage, which was driven by a crank through a connecting rod, the stroke being 4½ in and the length of the connecting rod 9 in. The speed of operation was 120 c/min, which corresponds to an average speed of 90 ft/min.

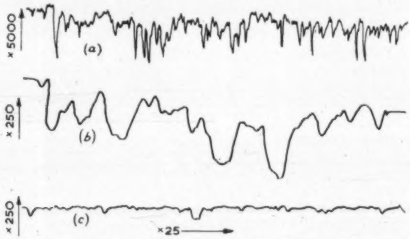

Fig. 1. Talysurf traces of steel surfaces. (*a*) Normal ground surfaces. (*b*) Normal seized surfaces. (*c*) Slowly worn surfaces

To eliminate errors due to possible progressive changes in material the specimens were selected on a randomized basis. The test pieces were each numbered in the order of manufacture. A set of random numbers was then divided into the six groups corresponding to the six treatments involved and the specimens treated accordingly. A random procedure was also adopted for pairing the upper and lower surfaces and the order of test was also randomized.

Results.—The results of some tests in which mild steel surfaces treated in various ways ran against ground mild steel are shown in Table 2.

Table 2. *Effect of lubricant and treatment of surface on wear and friction in reciprocating motion*

Treatment of lower surface	*No. of tests*	*Time to seizure (average)*	*Coefficient of friction (average)*
		Unlubricated	
Ground (5 μin average reading)	1	immediate	
Tin-plated	4	2 h	0·6
Chromium-plated:			
Polished	4	3 h 30 min	0·9
Mat	4	2 unseized but badly worn 2 4 min	1·0
Phosphated	4	1 h 35 min	0·7
		Lubricated with paraffin wax	
Ground	4	27 h	0·24
Tin-plated	4	35 min	0·4
Chromium-plated:			
Polished	4	unseized but badly worn	1·2
Mat	4	40 min	0·6
Phosphated	6	unseized in 50 h test, then ran smoothly under 200 lb load	0·17

The most critical factor was the time which a specimen would run without seizure. Seizure can be defined as complete failure of the surface accompanied by marked variations in friction. Examination of the surfaces after seizure revealed severe abrasion and roughening of the surface. Wear, on the other hand, usually resulted in a surface which was smoother than at the commencement of a test. The difference is illustrated in Fig. 1.

It will be clear that the phosphated surface, lubricated with paraffin wax, was the best combination, and that the efficiency of paraffin wax as a lubricant was markedly affected by the nature of the surface treatment given to the material. Indeed, in the case of tin-plate the unlubricated material gave a longer life than the lubricated material although lubrication did reduce the friction.

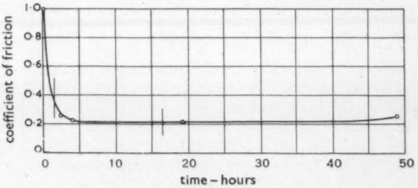

Fig. 2. Variation of coefficient of friction with time for phosphated surfaces lubricated with paraffin wax

Two of the four tests on the unlubricated mat chromium-plated surfaces were of interest in that, whilst the plated surfaces resisted seizure and were not subject to severe wear, they continually wore away the mating surfaces at a rate of about 0·001 in/h accompanied by the formation of quantities of reddish-brown powder. The resulting worn surfaces became extremely smooth. Lubrication was ineffective with chromium plate, presumably because its smooth surface did not provide reservoirs from which paraffin wax removed in the early stages could be replenished.

Where paraffin wax was used as a lubricant on a phosphated surface, friction was high initially but fell off with time of running in the manner indicated in Fig. 2. Fig. 3 shows a Talysurf trace of a phosphated surface before and after running for 50 h, and Fig. 4 shows similar traces taken from the corresponding untreated upper surfaces. Fig. 5 shows how the mean coefficient of friction of a phosphated surface lubricated with paraffin wax varied with load in a test carried out after 50 h running. Fig. 6 shows the friction-time oscilloscope records for three different loads. It will be noted that at the lowest load, 5 lb (= 67 lb/in²), there was no evidence of change in friction throughout the stroke. At a load of 100 lb (= 133 lb/in²) the friction-time curve was still square-shaped, but at 200 lb (= 267 lb/in²) the friction fell violently towards the middle of the stroke. It is suggested that under these conditions, frictional heat is sufficient to melt the wax and that hydrodynamic lubrication of a transient character results.

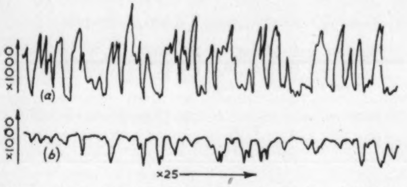

Fig. 3. Talysurf traces of phosphated surfaces. (*a*) Before running. (*b*) After running for 50 h lubricated with paraffin wax

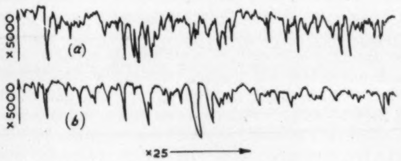

Fig. 4. Talysurf traces of ground surfaces. (*a*) Before running. (*b*) After 50 h running against phosphated surface lubricated with paraffin wax

DISCUSSION OF RESULTS

The suggested beneficial action of the paraffin wax in association with the phosphated surface is as follows. The anti-welding action of the phosphated surface enabled wear to occur at the initial stages without severe tearing occurring. The high initial values of friction were attributable to failure of the lubricant to be effective at the high spots. Sufficient paraffin wax was retained, however, in the irregularities of the surface to enable a layer to be formed on the surface after sufficient wear had occurred to ensure the necessary conformity between the two surfaces. It is suggested that after this state had been reached, normally in about 2 h, lubrication became completely effective.

It is further necessary to explain how paraffin wax is capable of acting as a lubricant at all. Bowden and Tabor have shown that thin metallic films enable low coefficients of friction to be attained.(3) It is possible that paraffin wax behaves in a similar manner. It is also possible that the wax might be orientated in the surface in the manner suggested by Brummage.(4) Another explanation is that the wax may have been melted locally by frictional heat to give rise to hydrodynamic effects. This is unlikely in the main experiment where the normal pressure was 6·7 lb/in², because temperatures were low, never rising more than 5° above ambient, and because the friction-stroke curve was always square-shaped. Had hydrodynamic effects been present reduction at high

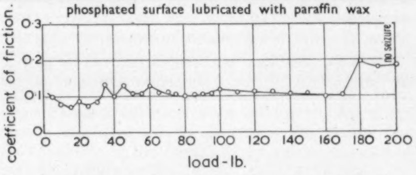

Fig. 5. Variation of coefficient of friction with load for a phosphated surface lubricated with paraffin wax

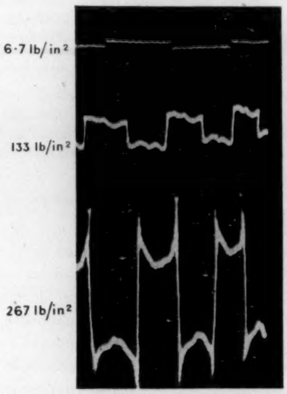

Fig. 6. Oscillograph records at three loads for phosphated surfaces lubricated with paraffin wax

speed would have been expected, as in Fig. 6, where the normal pressure of 267 lb/in^2 gave rise to quite different conditions. Had the wax been acting as a viscous fluid of approximately constant film thickness the friction-time curve would have been nearly sinusoidal in shape, viscous drag being proportional to rate of shear. The simplest hypothesis would appear to be that the wax had a sufficiently high yield value to prevent the surfaces from coming into contact and that it was sufficiently unreactive towards the metal to make easy the cleavage at the interface between itself and the mild steel upper specimen.

ACKNOWLEDGMENTS

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DISCUSSION

Mr. E. A. Smith: In a subject with so many variables and factors imperfectly understood, it is to be expected that this conference would produce features calling for criticism. Some of the papers presented, in themselves admirable examples of experimental work, were weakened by unsound conclusions. This led to some contradictions, if not stated, implied, as for example the work on solid lubricants reported by Dr. Barwell and Mr. Milne, and the experiments on the modified four-ball tester reported by Dr. Clayton. The former authors showed that graphite is an efficient lubricant measured in terms of friction values, while Dr. Clayton indicated that neither graphite nor colloidal graphite exerted any sensible or beneficial effect under his conditions of testing.

This apparent contradiction can be reconciled if one looks more closely into the matter. Dr. Barwell and Mr. Milne measured the friction of oriented layers of graphite between two metal faces. Dr. Clayton measured what he thought was graphite, but was, in reality, only the residual boundary oil film left by the graphited oil. In the first instance we have a real result; in the second instance the lubricant (graphite) was not there.

In the four-ball testing machine an extremely high initial load is achieved, which squeezes out the oil film. The latter would take with it the graphite particles, which in the time of testing with this machine, about one minute, would not attach themselves to the metal. Chemically active substances, such as chlorine, can be expected to react with a metallic face, speedily, so that the four-ball testing machine (or the modified form of it) might be expected to show up the value of such an additive.

The inference from the data of Dr. Barwell and Mr. Milne that graphite is an efficient lubricant is borne out by the measurements of friction shown in the table. To keep these values in practical perspective those for a graphite film in the presence of oil are also quoted:—

Test apparatus	*Conditions*	*Rubbing faces*	*Coefficient of friction*
Bowden–Leben	Dry film	Copper/copper and steel/steel	0·1–0·15
Simple 3-ball slider	Dry oriented film	Hardened steel/mild steel	0·19–0·15
Modified Deeley	Graphoid surface (oil free)	Mild steel/hardened steel	0·12
N. A.C.A.	Dry oriented film (very high rubbing speeds)	Normalized steel/hardened steel	0·14–0·20
Bowden–Leben	Colloidal graphite in mineral oil	Steel/steel	0·06–0·08
Deeley	Colloidal graphite in mineral oil	Steel/steel	0·04
Simple 3-ball slider	Colloidal graphite in mineral oil	Mild steel/hardened steel	0·08–0·09
Thoma	Colloidal graphite in mineral oil	Steel/steel	0·04–0·07
Metal rollers (for strip)	Colloidal graphite in soluble oil	Dural/brass	0·02
Experimental roll mill	Colloidal graphite in oil (extreme pressure)	Steel/brass	0·07

From the figures in the table it would be reasonable to conclude that the coefficient of friction for dry oriented films of pure graphite lies between 0·1 and 0·15, the nature of the substrate metal obviously playing no part if the coverage with graphite is complete. The comparatively wide spread of coefficients with graphite films in the presence of oil is to be expected, considering that all measurements relate to boundary conditions of lubrication, and the loads range from light load up to extreme pressures.

The corresponding friction values for mineral oil under similar test conditions would be 20%–50% higher, which indicates that the comparatively low values obtained with graphited oil are due, in a large measure, to the graphited surface formed on the metal. The latter, in the presence of a mineral oil film, yields a coefficient in the vicinity of that for stearic acid or mineral oil containing a high percentage of fatty oil.

From the heat of wetting of oil against graphite, and X-ray studies, one concludes that an oil film may adsorb more readily on a graphited metal than on a plain metal bearing face, while better spread, or wetting, is noted.

Trillat and Morel* have pointed out, recently, that flake graphite is ineffective in lubrication at greater rubbing speeds than a few centimetres per second, owing to the inability of the graphite particles to spread over the metal face. They draw attention to the necessity of forming an adsorbed graphoid surface with colloidal graphite.

The structure of the graphoid surface has been determined, notably by Finch, using electron diffraction. It is made up of an extremely thin film of graphite particles oriented with their basal planes parallel to the metal face on which they lie. Being adsorbed to the metal this slippery surface cannot be removed except by removing the substrate metal. Its presence can be detected by friction measurements.

In industry it is customary nowadays to use about 0·2% by weight of colloidal graphite in oil to assist the lubrication of new engines and mechanical equipment in general. In higher concentrations it is known to facilitate lubrication in metal extrusion and other chipless forming operations, while considerable use is also made of colloidal graphite in volatile liquids such as alcohol, to form dry, slippery films on metallic and non-metallic materials.

Dr. D. Clayton: I cannot accept Mr. Smith's suggestion of the way in which a graphited lubricant behaves in the four-ball apparatus: it is clear that the graphite does affect the results.

Dr. A. F. H. Ward: I should like to inquire about the method of application of the solid lubricants which were tested—whether these were added in one lot initially, or renewed continuously throughout the test. It would appear that the ease with which the powder was removed from the surface must be an important factor in determining its efficiency as a lubricant. In cases where there was no definite adhesion of the solid to the metal, the relative dimensions of the particles of the powder and the roughness of the surface might control the ease of removal of the powder.

Authors' reply: Mr. Smith is correct in pointing out that a great deal of confusion exists in specifying the relative merits of different methods of lubrication. This confusion is to some extent caused by failure of those who sell lubricants to specify the limits within which their products are beneficial.

There should be no grounds for confusion in comparison of results reported by Drs. Clayton and Jenkins and those in the present paper, because it is obvious that they were working in a region where extreme pressure properties were important, whereas the present paper deals with an entirely different set of circumstances. There is nothing in the present paper to indicate that graphite possesses qualities which, when used in an oil, would be any better than chemical additives, either of the polar or the E.P. types.

In reply to Dr. Ward we wish to report that in the friction tests, the lubricants were applied in the form of a powder sprinkled over the surface. There was only one traverse of the rubbing surfaces.

In the reciprocating experiments, the results clearly showed that for adequate life of the bearing surface some bonding or adhesion to the metal was essential.

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* TRILLAT and MOREL. *R. Inst. Français du Petrole*, **2**, p. 5 (1950).

The lubrication of rough steel surfaces by a series of metallic soaps

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This note describes the results of some friction experiments using metallic soaps, a fatty acid, an ester, and a straight-chain hydrocarbon, all of approximately equal chain length, to lubricate rough steel surfaces. The conditions of test covered a range of velocities and temperatures, but were confined to one set of surface conditions, namely a hard slider pressed against a soft plate with a roughness of approximately 50 μ in average reading.

For the metallic soaps, the relation between friction and velocity was a close approximation to an empirical law: log (friction) $\propto$ log (velocity) + a constant, over the range 0·001 cm/sec to 0·6 cm/sec. The agreement was less good for the ester and the hydrocarbon.

Comparing interpolated values of friction for the different conditions, the melting point of the solid lubricants was shown to be very critical, higher temperatures resulting in a sudden marked increase in friction. For greasy soaps, there was a continuous rise in friction over the range 25° C to 150° C. Differences in metallic ion or acid radical in the soaps had comparatively little effect on the friction other than that attributable to the physical state of the lubricant. There was evidence of progressive reaction with the metal surface in the case of the acid. The ester was a less effective lubricant than the soaps, while the hydrocarbon was a very poor lubricant.

Microscopic examination of the surface damage showed that the solid lubricants were very effective in separating the surfaces, contact occurring only at intermittent points. With the melted lubricants considerably greater contact took place. Surface profile records showed that contact was made only at the peaks of surface irregularities, which were depressed by an amount small compared with their initial height.

Metallic soaps form an important constituent in most mineral base greases. The main reason for their use is to act as a vehicle for oil but they have also a considerable influence on the boundary lubricating properties of the resultant grease. Further, Bowden has shown(1) that the good boundary lubricating properties of fatty acids are due to their ability to react with some metal surfaces with the formation of metallic soaps. A study of the effect of soaps on the friction between rubbing surfaces is therefore of considerable practical and theoretical importance.

Most of the earlier work on fatty acids and metallic soaps has been carried out using highly polished surfaces, an elaborate method of surface preparation and cleaning being followed to obtain good consistency of the results. Information is lacking, however, on the properties of these acids and soaps under different surface conditions. It has been shown by Barwell and Milne(2) that the conditions of the test may profoundly influence the results obtained and it was thought that some results obtained using specially roughened surfaces might be more applicable to many practical cases.

APPARATUS

The experiments were carried out on a kinetic boundary friction machine similar to that described by Bristow.(3) In this apparatus the friction is measured between a spherically-ended slider pressed against a flat plate moving rectilinearly at a constant velocity, the forces being measured by the deflexion of a heavily damped elastic system. Provision is made for varying the velocity and the temperature at which the measurement is made, and the results are presented as graphs showing the variations of coefficients of friction with change of velocity and temperature.

MATERIALS, METHOD OF SURFACE PREPARATION AND CONDITIONS OF TEST

Materials tested.—The substances used as lubricants in these tests were cupric oleate, lead oleate, cupric stearate (softening at 110° C), ferric stearate (softening at 90° C), stearic acid (M.P. 70° C), methyl stearate (M.P. 39·5° C), and docosane (M.P. 44° C). In all these the chain length is approximately the same. Most of them were tested as powders having either a well-defined melting point or a definite softening temperature. The two oleates, however, were greasy substances which merely became progressively more fluid as the temperature was raised. Commercially prepared metallic soaps usually contain an appreciable percentage of free fatty acid. For these experiments, therefore, the substances were specially prepared by the Chemical Research Laboratory, Teddington, to a very high standard of purity.

The rubbing surfaces were a low manganese-chromium oil-hardening steel. This was chosen because of the ease and the uniformity with which surfaces of different degrees of hardness, but of the same chemical composition, may be obtained. The lower plate was given a hardness of 200 H_{D30} and the upper slider a hardness of 850 H_{D30}.

Method of surface preparation.—In the experiments described in this note, it was thought that it would be of interest to study the effect of a very rough surface finish, even though this might lead to poor consistency of results. The lower plates were, accordingly, finished by lapping to a non-directional average roughness of 50 ± 5 μin as measured by a Talysurf instrument. The upper sliders were finished by polishing with 4/0 emery paper. The surfaces were then cleaned by scrubbing with cotton-wool soaked in caustic soda, rinsed in distilled water, and dried with acetone. The lubricant was spread thinly over the surface, which was heated just sufficiently to allow the lubricant to melt and to cover the surface completely and then cooled to room temperature.

Conditions of test.—Besides the factors mentioned above, other constant conditions of test included the radius of curvature of the upper contact, which was 0·5 cm, and the applied load, which was 8 lb.

For each plate and lubricant combination, friction-velocity determinations were made at 25°, 75°, 125°, 150°, 100° and 50° C, using a fresh portion of both the plate and the slider for each run. Friction was measured over a range of velocities from 0·001 cm/sec to 0·6 cm/sec.

RESULTS

Mode of presentation of results.—The results of tests were initially plotted as curves of friction against velocity (Fig. 1). In all cases four entirely independent tests were made, to give an estimate of the repeatability. The rough surface conditions chosen gave rise in some instances to a considerable scatter of results, this being most marked with docosane and methyl stearate. In these cases, it was sometimes difficult to decide on a suitable curve to draw through the plotted determinations. The metallic soaps, on the other hand, gave a reasonable consistency of results.

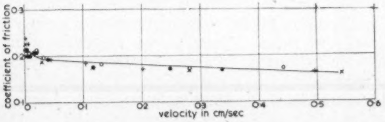

Fig. 1. Variation of coefficient of friction with velocity using lead oleate at 100° C as lubricant—plotted on linear scale

When plotted on logarithmic scales, the metallic soaps gave a very close approximation to a straight line. A typical result is given in Figs. 1 and 2, which compare the results of plotting on linear and logarithmic scales. On the linear scales, there is a rapid rise in friction at very low velocities, making interpolation at any low value of velocity difficult. On the logarithmic scales, however, an excellent approximation to a straight line is obtained. The linearity of this relation leads to the assumption that the relation between friction and velocity may be expressed by the empirical relation:—

$$\log(\text{coefficient of friction}) \propto \log(\text{velocity}) + \text{a constant}$$

There is as yet no theoretical justification for this expression, and it would be unwise to extrapolate the line beyond the limits of this experiment, i.e. 0·001 cm/sec and 0·6 cm/sec. Its assumption as a general rule, however, greatly facilitates the drawing of a line through a series of scattered points. Thus, Fig. 3 shows the results of the test for which the greatest scatter was obtained, docosane, at 25° C. Here the assumption of a linear relation on a logarithmic basis enables a best straight line to be calculated, which is more satisfactory than the drawing of a doubtful curve.

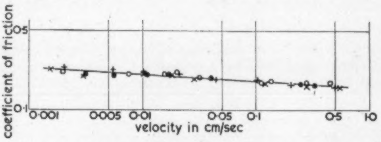

Fig. 2. Variation of coefficient of friction with velocity using lead oleate at 100° C as lubricant—plotted on logarithmic scale

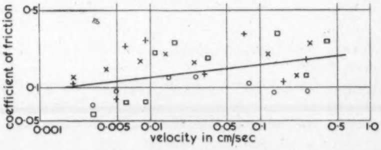

Fig. 3. Variation of coefficient of friction with velocity using docosane at 25° C as lubricant—plotted on logarithmic scale

For the comparison between lubricants, or between the same lubricant under different conditions, the logarithmic regression line has many advantages. The relation between friction and velocity is of the greatest importance under any given set of practical conditions, and this may be defined by two parameters. In the subsequent paragraphs, the results are all quoted as interpolated points from graphs drawn according to the above relation. The interpolated values are those at 0·01 cm/sec and 0·5 cm/sec.

The effect of metallic ions.—Figs. 4 and 5 show a series of interpolated values of friction, plotted against temperature, for copper and lead oleates. There is little difference between these two substances, and the friction for both rises steadily as the temperature

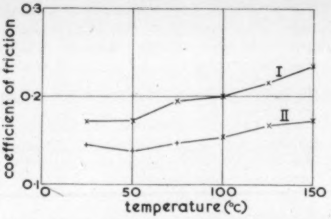

Fig. 4. Variation of coefficient of friction with the temperature using copper oleate as lubricant. Curve I, at 0·01cm/sec; Curve II, at 0·5 cm/sec

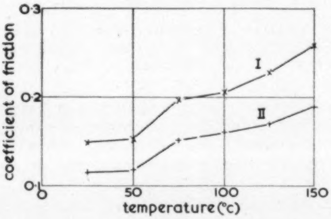

Fig. 5. Variation of coefficient of friction with the temperature using lead oleate as lubricant. Curve I, at 0·01 cm/sec; Curve II, at 0·5 cm/sec

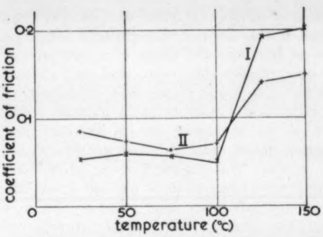

Fig. 6. Variation of coefficient of friction with the temperature using copper stearate as lubricant. Curve I, at 0·01 cm/sec; Curve II, at 0·5 cm/sec

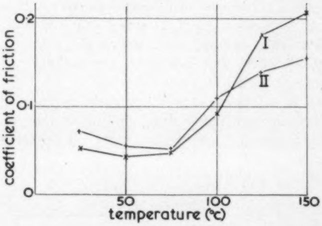

Fig. 7. Variation of coefficient of friction with the temperature using ferric stearate as lubricant. Curve I, at 0·01 cm/sec; Curve II, at 0·5 cm/sec

increases, slightly more rapidly for the lead than for the copper oleate.

Figs. 6 and 7 show similar curves for copper and ferric stearates. In this case, there is a marked discontinuity at the melting point for each, and the slope of the friction-velocity line changes sign. Apart, however, from the friction at 100° C, where copper stearate is solid and ferric stearate is molten, the differences between the two substances are small compared with the effect of temperature on each.

The effect of the acid radical.—A comparison of Fig. 4 with Fig. 6 indicates the effect of the acid radical on the friction. At temperatures above the melting point of copper stearate, there is little difference between it and copper oleate. At lower temperatures, however, where the stearate is solid and the oleate is greasy, there is a marked difference between the two.

Possible exchange of metallic ion.—The order in which the experiments were carried out at different temperatures was 25°, 75°, 125°, 150°, 100°, 50° C. In the curves previously shown there is no indication of any marked difference between the friction values obtained on rising temperature and those obtained during a decrease in temperature. In Figs. 4 and 5, however, there is a slight tendency for the friction at 50° C, and 100° C, to be slightly below the average line joining the points. There is the possibility that an exchange of metallic ions may be taking place between the lubricant and the metal surface. This effect is shown very markedly with stearic acid in Fig. 8. As usual, there is a discontinuity at the melting point. Further, there is a very low value for the friction at 50° C, which is the last set of readings taken. The value of the friction at this temperature is very similar to that of ferric stearate. Fig. 9 shows the result of an experiment in which the temperature was raised by increments of 25° from 25° C to 150° C, and then lowered to 75°, 50°, 25° C. It will be noted that there is a considerable difference at 25° C and at 50° C between measurements taken before and after heating to 150° C, and that the lower values obtained on cooling are very approximately similar to those obtained for ferric stearate. The points at 75° C are rather anomalous, but this may be due to the closeness of the temperature to the melting point of stearic acid (70° C). It is clear that there is a progressive reaction between the acid and the metal surface with the possible formation of the iron soap.

Methyl stearate and docosane.—It is possible that with the metallic soaps there has been some interaction with the surface. This is unlikely to happen with methyl stearate, and is certainly not the case with docosane, which is completely unreactive. Figs. 10 and 11 show the results of experiments with these substances. Again, there are marked discontinuities at the melting point, with subsequent steady increases in friction. The friction for the straight-chain hydrocarbon is considerably greater than that for the ester which, again, is greater than that for the metallic soaps. There is no evidence of any progressive change during the course of the experiment.

Surface damage by sliding.—Examination of the surfaces after sliding showed that contact had been taking place only over a very small portion of the nominal contact area. The amount of contact was considerably greater for the melted soaps than for the solid soaps. Typical differences are shown between Fig. 12, which shows a portion of the track on the lower surface when using copper stearate as a lubricant at 25° C, and Fig. 13, which shows a similar track, but at 150° C, at the same velocity, 0·1 cm/sec. The amount of intimate contact is seen to be very much greater. From surface profile records it is clear that the bright portions of the photographs indicate areas where the surface irregularities have been depressed; Fig. 14 shows a Talysurf trace of the track in Fig. 12. The depth of deformation is much less than the total irregularities of the surface, the peaks being removed and some of the hollows partially filled. The tracks exemplified in Fig. 12 were undetectable by surface profile examination. The amount of deformation was comparatively unaffected by lubricant or by velocity, the main differences being between solid and melted lubricant.

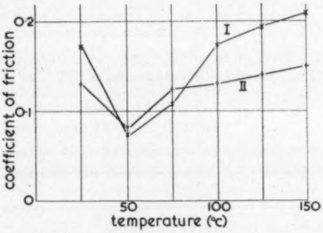

Fig. 8. Variation of coefficient of friction with the temperature using stearic acid as lubricant. Curve I, at 0·01 cm/sec; Curve II, at 0·5 cm/sec

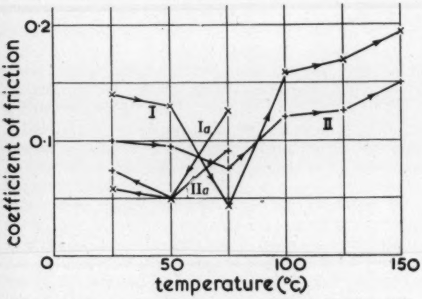

Fig. 9. Variation of coefficient of friction with the temperature using stearic acid as lubricant. Temperature raised by increments of 25° from 25° C to 150° C (curves I and II) and then lowered to 75°, 50°, 25° C (curves I*a* and II*a*). Curves I and I*a* at 0·01 cm/sec; Curves II and II*a* at 0·5 cm/sec

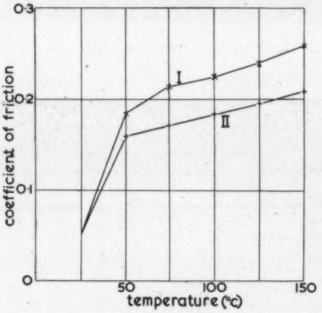

Fig. 10. Variation of coefficient of friction with the temperature using methyl stearate as lubricant. Curve I, at 0·01 cm/sec; Curve II, at 0·5 cm/sec

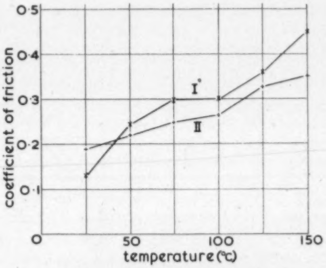

Fig. 11. Variation of coefficient of friction with the temperature using docosane as lubricant. Curve I, at 0·01 cm/sec; Curve II, at 0·5 cm/sec

DISCUSSION OF THE RESULTS

The results of these experiments show very clearly that, under these conditions at least, the physical state of the lubricant is of great importance. All the lubricants, when solid, gave comparatively low values of friction, and when fluid, gave comparatively high values. Those of a greasy nature, the oleates, were intermediate. Compared with these major differences, change of metallic ion or acid radical, except in so far as they affected the physical state, had only a small effect. It is clear that the solid lubricants are effective in separating the rubbing surfaces, while the fluid lubricants allow appreciable contact and deformation.

Fig. 12. Track on lower plate with copper stearate at 25° C (× 36)

Fig. 13. Track on lower plate with copper stearate at 150° C (× 36)

The above considerations indicate that the rheological properties of these lubricants may have considerable influence on the frictional behaviour. The chemical nature of the lubricant may only be important in so far as it governs the rheological properties of any products of reaction with the surface.

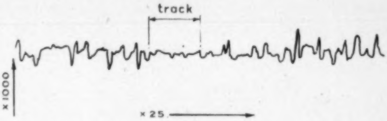

Fig. 14. Talysurf trace of lapped steel surface (average reading 50 μin) using copper stearate at 150° C as lubricant

ACKNOWLEDGMENTS

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The lubrication of metals by long chain organic compounds

By K. V. Shooter, M.A., Research Laboratory on the Physics and Chemistry of Rubbing Solids, Department of Physical Chemistry, University of Cambridge

The work of Bowden and his collaborators on the boundary lubrication of metals by fatty acids has shown that for efficient lubrication chemical reaction and soap formation must occur. More work has suggested that more than an adsorbed monolayer of soap on each of the sliding surfaces is required to produce a low coefficient of friction. An investigation has been made of the lubrication of several metals by a series of fatty acids. The friction results show that reaction and soap formation occur and that more than a monolayer of soap on each sliding surface is required for good lubrication

The importance of chemical attack in the boundary lubrication of metals by fatty acids and other long chain compounds has been emphasized by several workers in this field.[1-4] It has been shown that under conditions of boundary lubrication (low sliding speed and heavy load) non-reactive lubricants such as hydrocarbons and alcohols only provide effective lubrication up to the bulk melting point of the compound. With reactive metals lubricated by fatty acids the friction remains low, even above the bulk melting point of the acid. Lubrication persists because the acid reacts with the metal to form the higher melting-point soap. The breakdown temperature (the temperature at which lubrication fails and the friction increases) in such cases corresponds more nearly to the melting or softening point of the appropriate soap.

Tingle, working in this laboratory, has investigated the behaviour of metals lubricated by a solution of lauric acid ($C_{11}H_{23}COOH$) in paraffin oil.[5] On the basis of his results he has suggested that effective lubrication is only obtained when continued reaction between the metal and the lauric acid occurs, giving a thick film of soap between the sliding surfaces. Some confirmation of this thick film hypothesis has been provided by the work of Greenhill,[6] who has shown that, in general, three or more Langmuir-Blodgett monolayers of stearic acid, ethyl stearate and copper and silver stearate are required to give a coefficient of friction of 0·1 or less.

This paper emphasizes the importance of chemical attack and provides additional evidence for the view that polymolecular films of soap are necessary for the most effective lubrication.

In recent papers Zisman[7, 8] and his co-workers have shown that if a metal surface is covered with a solution of a long chain polar compound in an organic solvent, the polar compound is adsorbed on the metal surface, giving an oriented monolayer which is not wetted by the superincumbent solution, i.e. it is possible by this method to deposit a monolayer of a compound on a metal surface and then drain off completely the excess of solution.

Using this technique, monolayers of fatty acids have been deposited from solution in cetane (*n*-hexadecane) on surfaces of the reactive metals copper, iron, zinc, cadmium and magnesium, and the coefficient of friction in the presence of the monolayer measured using the Bowden-Leben apparatus.[9] Having deposited a monolayer on the flat surface, the hemispherically ended slider can be surrounded by a pool of solution; this deposits a monolayer of acid on the slider, the presence of the excess solution acting as a reservoir for the replenishment of the monolayer. It has thus been possible to measure the friction (*a*) with one monolayer of acid on the flat surface, and (*b*) with a monolayer on each of the sliding surfaces. The coefficients of friction μ measured are given in Table 1, which includes for comparison the dry friction and the friction in the presence of cetane. In every case the two sliding surfaces were of the same metal. The fatty acids used were of a high degree of purity and the metals spectroscopically pure.

The hydrocarbon cetane, which does not form an oriented monolayer on the surface of the metal, reduces the friction little if at all from the value for dry sliding. A monolayer (on the flat plate) of lauric acid or octacosanoic acid (C_{28}) does not reduce the friction of zinc, cadmium and magnesium. With iron and copper the coefficient of friction decreases with increasing chain length of the acid. The last column of Table 1 gives the coefficient of friction for a monolayer on each of the sliding surfaces. With iron there is no further reduction in friction, copper shows a still further decrease, and cadmium and magnesium a slight decrease with increasing chain length. The friction for zinc is not reduced.

The temperatures at which lubrication fails have been determined for iron and copper. The transition temperature for one monolayer on iron lies between the melting point of the acid and of the soap; for a monolayer on each of the sliding surfaces the temperature corresponds approximately to the melting point of the soap. For two monolayers on copper the transition temperature corresponds to the melting point of the acid. Although these results suggest that only on iron does reaction and soap formation occur, the weight of other evidence is that soap formation has occurred on all the metals. Menter,[10] using the electron diffraction technique, has shown that monolayers of acids deposited in this manner on these metals persist above the melting point of the acid. With copper a reorientation of the soap monolayer occurs at about the melting point of the acid. These points are further elaborated by Menter in his paper. Zisman and others(8) have shown that monolayers of fatty acids on the unreactive platinum only exist to temperatures slightly higher than the melting point of the acid; above these temperatures the monolayer redissolves in, and is melted by, the superincumbent solution. The monolayers of fatty acid on the metals examined in this investigation remain unwetted to temperatures well above the melting point of the acid. This can only mean that reaction and soap formation has occurred. Further, if the monolayer is acid, then it should only be as effective in reducing the friction as a monolayer of a non-reactive polar compound of the same chain length, but on copper, for example, a monolayer of octadecanol gives a coefficient of friction of $\mu = 1\cdot0$, compared with $\mu = 0\cdot35$–$0\cdot5$ for stearic acid. The general conclusion is that a monolayer of soap on each sliding surface is not sufficient to give a low coefficient of friction except for iron and the longer chain length acids on copper.

But if instead of the cetane solution of fatty acid the neat acid is used as a lubricant, much lower coefficients of friction and higher transition temperatures are found. Or, as Tingle(5) has shown, if the metal surface is subjected to some fairly specific treatment before application of the solution of acid, low coefficients of friction can again be obtained. In Table 2 some of the results from Table 1 are compared with results obtained using these treated surfaces. The treatment described in the table does not affect the dry friction or the friction in the presence of cetane. The low coefficients of friction can only be explained if it is assumed that a thick layer of soap is formed between the surfaces as a result of continued reaction, e.g. if the coefficient of friction for copper with a monolayer of copper laurate on each surface is 0·3–0·6, to reduce the friction to 0·05 more than two monolayers of copper laurate must exist between the two surfaces.

The solubility of the metal soaps of the saturated straight chain fatty acids in cetane is extremely small; if continued reaction did occur soap would quickly precipitate out on the surface, producing a thick lubricating film.

This evidence for the continued reaction and the formation of thick films of soap is indirect; in his paper Moore(11) will adduce more direct evidence in favour of the hypothesis.

Table 1. *Coefficients of friction for some metals*

	Dry friction	*Pool of cetane round slider*	*Monolayer of acid on plate*	*Pool of cetane solution of acid round slider*
Copper	1·4–1·6	1·2–1·4	(12) 0·9–1·0	(12) 0·3–0·6
			(14) 0·4–0·6	(14) 0·1–0·15
			(18) 0·35–0·5	(18) 0·1–0·15
			(28) 0·25–0·35	(28) 0·1–0·15
Iron	0·6	0·7–1·0	(12) 0·15–0·25	(12) 0·1–0·2
			(18) 0·1–0·3	(18) 0·06–0·13
			(28) 0·1	(28) 0·1–0·2
Magnesium	0·5–0·6	0·4–0·6	(12) 0·3–0·4	(12) 0·45
				(18) 0·25–0·3
			(28) 0·35	(28) 0·2–0·3
Zinc	0·6	0·4–0·5	(12) 0·4–0·5	(12) 0·35–0·45
			(28) 0·3–0·4	(28) 0·4–0·45
Cadmium	0·5–0·6	0·3–0·35	(12) 0·4–0·5	(12) 0·25–0·3
				(18) 0·25–0·35
			(28) 0·4–0·5	(28) 0·15–0·2

The figures in brackets are the number of carbon atoms in the fatty acid.

Table 2. *Coefficients of friction after water treatment*
[Lubricant: pool of lauric acid (M.P. 43° C) in cetane]

	Friction on untreated track	*Breakdown temperature, °C*	*Water treatment*	*Friction on treated cut track*	*Breakdown temperature, °C*	*M.P. of metal laurate, °C*
Copper	0·3–0·6	40	Washed 2 min boiling water	0·05	110	110
Magnesium	0·3–0·4	—	Washed 2 min boiling water	0·1	150	160
Cadmium	0·4–0·5	—	Washed cold water	0·05	90	—
Zinc	0·4–0·5	—	Washed with hot water	0·05	130	130

ACKNOWLEDGMENTS

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DISCUSSION

Dr. A. F. H. Ward: In connexion with the formation of adsorbed films of fatty acids on metal surfaces, I should like to draw attention to a relevant phenomenon. It has recently been shown that for the adsorption of long-chain fatty acids from an organic solvent on to the interface with water there may be a considerable delay before the adsorbed layer is complete.(1) Adsorption is initially rapid, but up to half an hour may be required to reach complete saturation. It is reasonable to expect similar behaviour for the adsorption of fatty acids from a solvent on to a metal surface. This might be shown by a value for the coefficient of friction which depended on the time interval before the friction was measured and after the application of the solution to the surface; though the variation should be most marked in the very early stages of the adsorption. But whether or not this slow adsorption can be detected by friction measurements, it should have an important effect in cases where the lubricant film is broken locally in incipient seizure. The extent to which the surface layer of lubricant is restored in a very short time (a small fraction of a second) must determine whether the film is progressively diminished or whether the restoration can keep pace with the loss. Under such conditions the speed of adsorption may well be the dominant factor for the efficiency of the lubricant.

Author's reply: The slow attainment of adsorption equilibrium mentioned by Dr. Ward has also been noted by Zisman,(2) who has shown that the time for the formation of an oleophobic monolayer increases as the concentration of the solution decreases. In his heat of adsorption measurements Daniel(3) has shown that the adsorption of a fatty acid on to a metal powder occupies several minutes. In the experiments described in my paper the monolayers were formed in a few seconds; no measurements of the friction during the formation of the monolayer were therefore possible. In my paper it is shown that the adsorbed monolayer of fatty acid or soap does not itself give a very low coefficient of friction.

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A study of boundary lubricant films by electron diffraction

By J. W. MENTER, M.A., Ph.D., A.Inst.P., Research Laboratory on the Physics and Chemistry of Rubbing Solids, Department of Physical Chemistry, University of Cambridge

The paper describes work carried out by the author and other workers in this laboratory on the orientation and structure of thin films of long chain hydrocarbon compounds on metal surfaces. The effect of temperature has been investigated and results obtained correlated with frictional behaviour of sliding surfaces lubricated with the same compounds. It is concluded that good boundary lubrication occurs only when there is a closely packed solid film of oriented molecules on the surface.

A study of the effect of temperature on the orientation of the molecules in thin layers of long chain hydrocarbon compounds on metal surfaces is of some importance for elucidating the mechanism of boundary lubrication. Previous work using electron diffraction techniques has been confined mainly to the study of multimolecular layers,(1) or a limited number of materials(2,3). A new investigation has recently been undertaken in which interest has been directed towards the behaviour of the first monolayer adjacent to the metal surface. A wide range of materials and metal surfaces has been investigated.

A standard procedure was adopted for the preparation of the surface and for the deposition of a monolayer of the material to be studied. Fuller details of the experimental procedure may be found in the literature.(4,5,6)

The author has investigated the behaviour of layers of lauric, myristic, palmitic, stearic and octacosanoic acids and certain metal soaps on metallographically polished surfaces of platinum, silver, copper, zinc, cadmium, mild steel and nickel. It was found that the first monolayer was oriented with the hydrocarbon chains approximately normal to the surface; the longer the chain, the better the orientation. Material above the first monolayer generally showed a different orientation and structure. These observations are in agreement with those of other workers. The structure of the monolayer was unaffected by rubbing except in the case of octacosanoic acid, where it was found that the hydrocarbon chains tilted to an angle of about 15° from the direction of the surface normal and were alined in the direction of rubbing.

On heating it was found that the diffraction pattern remained unchanged for a considerable rise in temperature but then became increasingly diffuse as the temperature was raised further, indicating an increase in the thermal motion of the molecules. At a critical temperature, characteristic of the material of the surface film and the chemical nature of the metallic surface, the diffraction pattern disappeared completely, showing that the regular orientation was entirely destroyed and two-dimensional melting of the film may be said to have occurred. On cooling the oriented pattern reappeared, indicating that the transition was reversible.

With fatty acid films on non-reactive metals such as platinum, the transition temperature was close to the bulk melting point of the acid. On reactive metals, however, the orientation persisted up to a much higher temperature. Both the structure and orientation were similar to those observed with a thin film of the corresponding metal soap, and the evidence directly supports the view that chemical reaction occurs between the fatty acid and the surface. Thus the first monolayer on a reactive surface consists of the metallic soap.

With non-reactive long chain polar compounds such as alcohols and esters, Sanders and Tabor(6) have shown that the first monolayer is strongly oriented at room temperature but loses its orientation at a temperature close to its bulk melting point. This occurs on both reactive and non-reactive metals. With some specimens of esters, however, a different behaviour was observed. On reactive metals orientation persisted up to temperatures well above the melting point of the ester. In fact, the behaviour was similar to that observed with fatty acids and suggested that small quantities of fatty acid were present as impurity, or were formed by hydrolysis, at the metal surfaces.(7) This conclusion was confirmed by some experiments with radioactive foils.(10)

Measurements of the variation with temperature of the coefficient of friction between sliding surfaces lubricated under boundary conditions by these hydrocarbon compounds show that for a considerable temperature rise sliding is smooth, the surface damage small, and the coefficient of friction low (of the order 0·05–0·1). (See, for example, Tabor,(8) and Bowden, Gregory and Tabor.(9)) However, at a temperature characteristic of the lubricant and the metal, the friction suddenly increases, sliding becomes intermittent on account of direct intermetallic seizure, and the surface damage becomes much greater. It has been found that this transition temperature is very close to the disorientation temperature observed in the electron diffraction experiments. Thus the lubricating properties of long chain hydrocarbon compounds are closely connected with the structure and orientation of the lubricant molecules immediately adjacent to the surface. When the layer is well oriented the lateral attraction between the hydrocarbon chains is able to prevent appreciable metallic contact through the lubricant film. When the orientation is destroyed by thermal motion, the lateral attraction ceases to be effective, the monolayer loses its rigidity and increased metallic contact occurs. Thus the essential requirement of a good boundary lubricant is that it should form a *solid* film on the surface which, while offering little resistance to shearing forces, will resist penetration in a direction normal to the direction of sliding.

ACKNOWLEDGMENTS

I thank Dr. F. P. Bowden and Dr. D. Tabor for their advice and encouragement, the Ministry of Supply (Air) for grants for equipment, and the Department of Scientific and Industrial Research for a maintenance grant.

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DISCUSSION

Dr. K. H. R. Wright: The results obtained by Dr. Menter are of considerable interest as they conflict with those given by Brummage, who carried out similar experiments to determine the disorientation points of long-chain paraffins, fatty acids and esters deposited in the form of thin films upon metal substrates.

Brummage found that the disorientation point was invariably lowest for a monolayer and increased to a steady characteristic value which may be above or below the melting point of the material constituting the film. Although Dr. Menter did not investigate this relationship between the disorientation temperature and the number of molecular layers present, the values given by him in his paper for a monolayer deposit are very different from those obtained by Brummage, and in certain cases the monolayer disorientation temperature was greater than the temperature obtained by Brummage for very thick films. A comparison of some of the results obtained by both workers is given in the following table:—

		Disorientation point (°C)		
		Menter	*Brummage*	
Lubricant	*Surface*	*Monolayer*	*Monolayer (Extrapolated)*	*Upper limit < 50 layers*
Stearic Acid	Silver	85	52	100
	Mild steel	125	50	105
	Cadmium	130	85	100
	Copper	80	80	108

The discrepancies between the two sets of results might be due to the different methods employed in obtaining the thin films. Dr. Menter obtained his monolayers by the use of the Zisman technique, whereas Brummage used both the methods of direct deposition and, in the case of polar compounds, the Langmuir–Blodgett technique. However, if it is to be argued that the latter author could not be sure of the number of layers deposited then one would have expected that there would have been a considerable scatter in his results; yet this is not observed, and indeed the form of the relationship obtained is remarkably consistent from one material to another.

These results, therefore, indicate that our knowledge of the disorientation points of thin films of long-chain aliphatic compounds is not complete, and I would like to know whether Dr. Menter can give any reason for the discrepancies between his results and those of Brummage.

Mr. F. R. Dean: How is it certain that a monolayer is uniform and that there is no bunching of molecules in some places and gaps in others?

Author's reply: I am glad to have this opportunity of paying tribute to Brummage's valuable and pioneering work in this field. The experimental technique of the present investigation differs from his in three main respects.

(1) The technique of adsorption at the solid surface from the melt is not open to the same uncertainties as that of deposition from a volatile solvent employed by Brummage. There is strong evidence that the present technique gives a well-defined monolayer (cf. Bigelow, Pickett and Zisman,[1] and Courtney-Pratt[2]).

(2) The changes in the diffraction pattern are recorded photographically (up to 15 exposures in the course of one experiment) so that uncertainties inherent in the visual observations of the screen are largely eliminated.

(3) The experiments have been carried out with a wider and more representative range of materials. (For fuller details see Menter and Sanders,[3] Menter and Tabor,[4] and Sanders and Tabor.[5])

It is quite true that different methods of depositing the layers give different values for the transition temperature. For instance, vigorous rubbing of the fatty acid layer after deposition on a reactive metal raises the transition temperature. This may be due to better alinement of the molecules or to a more complete reaction since very little difference is observed between the two methods using a platinum surface (see Menter and Tabor[4]). The figures given by Dr. Wright refer to this rubbing technique. A more appropriate comparison would be with the layers formed by retraction. In this case the discrepancy with the results of Brummage is not so great. Further, as Dr. Wright has indicated, some of

Brummage's "monolayer" results are obtained by extrapolation in a region where, according to Brummage's own observations, the transition temperature is changing very rapidly with the thickness of the layer.

In reply to Mr. Dean I wish to say that it is already known that the area of a compressed monolayer removed from a Langmuir trough by dipping is equal to the apparent area of the specimen, so that one imagines that the layer is suspended across the surface asperities. Thus the layer is probably "uniform" and close packed immediately after deposition. It has been pointed out previously by Bikerman⁽⁶⁾ that Langmuir–Blodgett layers show a tendency to recrystallize even at room temperature. This is not surprising in view of the strains inherent in such a system and the possible ebullition of occluded water from the layer when placed in a vacuum. A few experiments by the author using this method, in fact, supported this conclusion, and the Langmuir–Blodgett method was therefore not employed.

With the retracted layers formed by the Zisman technique the exact nature of the adsorbed layer is uncertain. For a layer adsorbed from solution, Bigelow, Pickett and Zisman⁽¹⁾ have calculated an area of 30 A^2 per molecule assuming the apparent area of the surface is covered. This would indicate, in this case, that the molecules are not closely packed. However, the assumptions on which the calculation is made are open to question. For example, the effects of occluded solvent molecules are not considered. It is likely that a layer adsorbed from the melt is more closely packed, although there is no direct evidence to support this.

In the electron diffraction experiments only the molecules at the surface asperities give rise to the diffraction pattern. The pattern shows that the hydrocarbon chains are parallel to the surface normal to within a few degrees. This suggests that the molecules are closely packed, although it gives no evidence of how far this packing extends down the slopes of the asperities.

Examination of monolayers by the transmission technique will give further information on the lateral spacing of the hydrocarbon chains and work is in progress on this problem.

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The adsorption of lubricant films: a study by radioactive tracers

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The chemical reaction between radioactive metal surfaces and adsorbed monolayers of stearic acid, ethyl stearate, and octadecyl alcohol has been investigated. It is directly verified that when reaction occurs then the system exhibits good lubricating properties at temperatures above the bulk melting point of the lubricant up to the softening point of the soap. If no reaction occurs lubrication is only found below the bulk melting point of the lubricant. Reaction, when it does occur, does not cease with the formation of a monolayer of soap on the metal surface. If sufficient materials are present thick films of soap are built up.

Other contributors to this symposium[1, 2] have shown how the results of experiments on the structure of monolayers as revealed by electron diffraction methods and their lubricating properties are best explained by the theory due to Bowden, Gregory and Tabor[3] that, in appropriate cases, reaction occurs between the adsorbed layer and the underlying metal. The evidence in support of this is, however, indirect and it is proposed in this contribution to describe some direct evidence in support of the theory.

The direct method is obvious—deposit a monolayer on the metal surface, wash it off and then test the wash for the presence of metal. The weight of metal involved is of the order of 10^{-7} g/cm^2 of true surface area, and hence either a large surface area must be used (as in powders) or a sensitive method of detection is necessary. The latter method was adopted and, by making the metal surfaces artificially radioactive, adequate sensitivity of detection was obtained using only a few square centimetres of metal foil, with the certainty that all the metal must have originated in the radioactive foil. A brief account of some of these experiments has been given elsewhere.[4]

EXPERIMENTAL DETAILS

Metal foils of spectroscopic purity and 10^{-3} cm thick, made radioactive by neutron irradiation in one of the Harwell piles, were used. Their surface area was

Comparison of the properties of adsorbed films on metal surfaces

Metal	*Adsorbed film*	*Reaction with radioactive metal foils*	*Friction transition temperature*	*Electron diffraction disorientation temperature*	*Heat evolved after initial heat of adsorption*	*Slow adsorption after initial adsorption*
Platinum	Stearic acid	No	Low	Low	No	No
	Ethyl stearate	No	Low	Low	No	No
	Octadecyl alcohol	No	Low	Low	No	No
Gold	Stearic acid	No	—	—	—	—
	Ethyl stearate	No	—	—	—	—
	Octadecyl alcohol	No	—	—	—	—
Zinc	Stearic acid	Yes	High	High	Yes	Yes
	Ethyl stearate	Yes	High	High	—	—
	Octadecyl alcohol	No	Low	Low	No	No
Cadmium	Stearic acid	Yes	High	High	Yes	Yes
	Ethyl stearate	Yes	High	High	—	—
	Octadecyl alcohol	No	Low	Low	No	No
Copper	Stearic acid	Yes	High	High	Yes	Yes
	Ethyl stearate	Yes	High and Low	High and Low	No	No
	Octadecyl alcohol	No	Low	Low	No	No

limited to a few square centimetres after a consideration of the radiation hazards. Detection and estimation of the radioactive metals was carried out in solution using commercial thin-walled Geiger-Müller counter tubes. The electrical circuits were designed for long- as well as short-term stability and also to reduce electrical interference. The amount of metal in a given solution was estimated by comparing its radioactivity with that of a standard solution of the same radioactive metal specimen in a similar concentration. This method eliminates many sources of error.

Adsorbed layers on the surfaces of the metal foils were washed off in a Soxhlet continuous extraction apparatus with boiling benzene, and concentrated in the flask of the Soxhlet condenser.

The true surface area of the metal foils for adsorption was measured by W. R. Throssell,(5) using a microbalance, and was from three to five times the apparent area. An estimate of the amount of metal in an adsorbed monolayer of soap was made from the true surface area of the piece of foil used, assuming each soap molecule to occupy 20 A^2.

RESULTS

In the first series of experiments the metal foil, after washing until clean in boiling benzene, was immersed in a benzene solution of stearic acid (1%), octadecyl alcohol (2%), or ethyl stearate (5%), for five minutes and then withdrawn. Zisman and others(6) have shown that, under these conditions, an oleophobic monolayer is deposited on non-reactive surfaces such as platinum or glass. The adsorbed layer was washed off the foil and both the wash and the original solution were tested for radioactivity. The foil was then replaced in the original solution and after further intervals of time withdrawn and the tests repeated.

Platinum and gold, after being cleaned in concentrated nitric acid, did not react at all. No radioactivity was found either in the original solution or in the adsorbed layers washed from off the surfaces. About 10^{-9} g of gold would have been detected and a monolayer of soap would contain 100 times as much gold. Zinc, cadmium and copper did not react with octadecyl alcohol but all three reacted with a solution of stearic acid and to a lesser extent with a solution of ethyl stearate.

It appears that reaction when it occurs does not cease with the formation of a monolayer of soap on the metal surface, but that a thick film of adsorbed soap builds up. At the same time soap dissolves in the solution and may even, as in the case of copper, form a saturated solution and be precipitated out.

Further experiments were carried out by depositing Langmuir–Blodgett monolayers of stearic acid on to radioactive copper surfaces. Such layers are stretched over the surface resting only on the asperities. A detectable reaction did not occur unless the system was heated or left for several hours, when it is known(7) that the stretched film collapses. Reaction then appears to be complete.

These results were compared with an independent series of lubrication measurements which were carried out using the Bowden–Leben apparatus.(8) Thick layers of stearic acid, octadecyl alcohol, or ethyl stearate were deposited from the benzene solutions on to the metal surfaces. In all cases a transition temperature was observed below which smooth sliding with a low coefficient of friction existed. Above the temperature, intermittent (stick-slip) sliding occurred with a high coefficient of friction. The transition temperatures were very close to the bulk melting point of the lubricant when reaction did not occur in the corresponding experiments with radioactive metals. When reaction was shown to occur, then the transition temperature was higher than the melting point of the lubricant and near the softening point of the appropriate soap.

CONCLUSIONS

The results of electron diffraction observations of adsorbed monolayers of stearic acid, octadecyl alcohol, and ethyl stearate, by Menter and Sanders,(9) are in good agreement with the results of the radioactive and lubrication experiments, a low disorientation temperature of the monolayer being associated with no reaction with the radioactive metal. Measurements by Greenhill(10) and Daniel(11) of the adsorption and the heats of adsorption of stearic acid, octadecyl alcohol, and ethyl stearate on metal powders are also in close agreement with the radioactive results. When reaction has been shown to occur then after the initial adsorption of the compound on to the powder, there follows a slow continuous adsorption accompanied by a slow evolution of heat.

The only anomaly is found in the behaviour of ethyl stearate on reactive metals. This can be explained by the presence of a small trace of acidic impurity. If all the reaction between radioactive copper and ethyl stearate is attributed to a stearic acid impurity then the amount of acid present can be estimated. This proved to be 9×10^{-5} g in 1 g of ester. Under the conditions of the lubrication and electron diffraction experiments there is enough acid present to form four or five monolayers of soap on the metal surface.

A fresh sample of ethyl stearate, which was shown by experiments with radioactive copper to contain insufficient acid to form a monolayer of soap in the friction and electron diffraction experiments, behaved as if it were inert except on zinc and cadmium. It is possible that here a reaction is taking place involving the metals and the ester. Neither samples of ester contained enough acid to show up in the adsorption experiments on metal powders.

All these results are summarized in the table.

ACKNOWLEDGMENTS

I should like to thank Dr. F. P. Bowden for his continued advice during the investigation. I have also pleasure in thanking King's College, Cambridge, for an Open Foundation Scholarship, and the Department of Scientific and Industrial Research for a maintenance grant.

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DISCUSSION

Dr. W. Hirst: As Dr. Moore has mentioned, there are two methods available for studying the reaction between fatty acids and the outer molecular layers of a metal or metal-oxide: (*a*) to use a powder of large specific surface area so that a reaction producing a single monomolecular layer of metal soap involves sufficient material to enable ordinary analytical methods to be used for its detection, and (*b*) to use smaller surface areas, e.g. metal foils, and a more sensitive method of analysis. Dr. Moore has chosen the latter method. In the Research Laboratory of Associated Electrical Industries Ltd. my colleague Mr. Lancaster has been studying the reaction between stearic acid in benzene solution and a number of metal oxides, using the powder method. The surface areas of the powders having been measured in subsidiary experiments, the experimental procedure involved was to determine the amount of acid removed from solution by the powder. When this quantity exceeded the calculated quantity required to cover the surface of the powder with a mono-molecular layer of acid it was concluded that chemical reaction was taking place. In general, Mr. Lancaster's observations support those of Dr. Moore, but it was also observed that the results obtained depended on the extent to which the powder and solutions were dried before use. Thus, using cuprous oxide which had been previously exposed to water vapour chemical reaction began immediately, whereas, when carefully dried powder and solutions were used, the amount of acid removed from solution reached a limiting value in a few minutes and remained constant throughout the following five hours. When water was added to the dried solution to a concentration of 1 part in 10^5, there was an induction period of about one hour after which rapid reaction began.

The following solids have been examined: copper, cuprous and cupric oxide, zinc and zinc oxide. With all these powders the quantity of water present in the system affected the reaction rate, and the suggestion arose that under dry conditions stearic acid is physically adsorbed, and that chemical reaction does not begin until a certain minimum concentration of water had diffused to the surface. To test this hypothesis, Mr. Rouse and Mr. Lancaster have measured the energy of interaction between stearic acid and the above powders using a calorimeter. With each powder under dry conditions the total heat liberation was complete within five minutes. The magnitude of the heat evolved indicates that the fatty acid is physically adsorbed on the surface. When the powders had been previously exposed to water vapour, the calorimetric results were of a completely different character. With the three powders, zinc, zinc oxide and cuprous oxide, there was a large initial heat liberation (of the order of 5 times that observed when the powders were dry), followed by a progressive heat liberation still continuing after several hours. With the other powders, copper and cupric oxide, this large initial heat was not observed, but the progressive heat liberation was such that after some hours it exceeded the value which had been obtained using dry powders. These measurements of interaction energies leave little doubt that, when sufficiently dry conditions are obtained, stearic acid is adsorbed physically on the above solids.

The quantity of water required to cause reaction between a fatty acid and a metal oxide depends on the metal and also on the nature of the oxide. For example, striking differences have been observed between the behaviour of cupric and cuprous oxide and the oxide film on copper powder which has been exposed to the air. This observation is in accord with that of Dr. Tingle who found that for reaction to occur it is necessary to "condition" freshly prepared metal surfaces with water and that this water treatment varies greatly with the metal. A fuller account of the work has been submitted for publication elsewhere, but it is hoped that this summary will serve to direct attention to the influence of traces of water on the onset of reaction between stearic acid and metal oxides. Once started, the reaction itself produces water and the effect of extraneous water is presumably then of less importance.

Mr. A. J. Chisholm: In connexion with the lubrication of sliding surfaces by the formation of a low shear strength substance at the interface by chemical reaction, the work carried out by those concerned with the behaviour of fluids used in the machining of metals may be of interest.

Ernst and Merchant reported(1) that fluids causing a reduction in the friction coefficient between the cutting tool and the chip sliding over it seemed to react directly with the clean surface of the metal to form a low shear strength material. In experiments cutting aluminium, using carbon tetrachloride as a cutting fluid, the speed was adjusted to such a low value that it was possible to collect sufficient of the reaction product to identify it chemically as aluminium chloride.

M. C. Shaw(2) has suggested that the ability of substances to react with metals when a clean surface of the metal was exposed by cutting, might be utilized to prepare organometallic compounds where synthesis—the normal method of preparation—was difficult to initiate. Shaw has carried out experiments in which this view has been confirmed.

It seems that the metal cutting process may prove to be a useful tool for studying the behaviour of boundary lubricants because the area of clean metal surface which can be exposed to chemical attack is comparatively large, and the products of the reaction may be sufficiently bulky to be identified by normal chemical means.

Author's reply: The results of the experiments by Hirst and Lancaster give very strong but indirect evidence for chemical reaction in the appropriate cases. Similar results were obtained with metal powders by Greenhill(3) and Daniel.(4)

In the radioactive experiments described above, the benzene used for washing the metal foils and making up solutions of the organic compounds was dried by storing, refluxing and redistilling over metallic sodium. It would be difficult, however, to eliminate the last traces of water, and whereas such traces would not show any effect in relatively large scale powder adsorption measurements, they might well affect the radioactive and lubrication experiments. In the case of cadmium the addition of excess water to the solution did not noticeably affect the reactions.

A method similar to that suggested by Mr. Chisholm for adapting a metal cutting process to study the behaviour of boundary lubricants has been used by Tingle.(5) He found that, under the conditions of his experiments, both oxide and water were necessary for reaction to take place between a "metal" surface and an appropriate lubricant.

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The spreading behaviour and lubricating properties of mixed liquids

By E. B. Bielak, B.Sc., E. W. J. Mardles, D.Sc., F.R.I.C., and E. D. Tingle, Ph.D., Royal Aircraft Establishment, Ministry of Supply, S. Farnborough, Hants.

Measurements of the rate of radial flow of several liquids and their binary mixtures over or between various polished surfaces have been correlated with friction results on the same surfaces. The results have been presented in graphical form relating composition of the binary mixture with the properties of friction and spreading. Divergences from the simple mixture law, sml $\mu \sim \mu$, where sml μ represents the friction calculated from the observed values of the single constituents of the binary mixture and μ the observed friction value are shown together with similar divergence values for spread, sml $d \sim d$, in terms of the size (diameter, radius or their logarithms) of a pool after a period of time.

Changes in the molecular association of the liquids on admixture appear to account for the observed behaviours.

A method of measuring the radial flow of lubricants over and between polished surfaces has been developed,[(1)] and the results of these spreading tests have been correlated with those of friction on the same surfaces.

The results have been expressed graphically, showing the divergence from the simple mixture law illustrated in Fig. 1; and it will be seen that where the surface activity is above the simple mixture value the friction is correspondingly lower. It appears that when with change of composition the molecular association is increased (and consequently the activity of the mixed liquid for the solid surface decreased) there is a fall in the rate of spreading and an increase in the coefficient of friction.

EXPERIMENTAL RESULTS

The surfaces of the polished flats were washed and polished under water with rouge, then rinsed with a jet of hot distilled water and finally polished with soft lint. The cleaning and polishing were done immediately prior to use. A known volume of liquid up to 1 ml was delivered to the centre of the horizontal plate and its rate of spread was determined by measuring the diameter from time to time or, if the shape of the pool became irregular, by using a planimeter. After placing a glass flat of known weight upon the liquid pool the rate of radial flow between the flats can be measured in the same way. The friction of flat sliders was measured from the tangential force required to begin movement or to sustain movement at a prescribed rate. Both the methods of tilting and of using a load acting over a light pulley were employed. In the friction tests, about an hour was allowed for the oil to wet the surface thoroughly and for the flat to sink into the pool of lubricant. On the curves correlating spread with friction, values for the spreading have been expressed as *differences* of diameter or radius (or their logarithms) of the pool of a known volume and that obtained from the simple mixture law (sml). The following notation has been used:—

μ_s = Coefficient of static friction.
μ_k = Coefficient of kinetic friction.
sml μ_s = Coefficient of static friction using a mixed lubricant and calculated by the simple mixture law.
sml μ_k = Coefficient of kinetic friction using a mixed lubricant and calculated by the simple mixture law.
d = Diameter of pool of lubricant.
sml d = Diameter of pool of a binary mixture calculated by the simple mixture law.

The friction results are at pressures less than 100 g/cm^2 unless otherwise stated, and for this reason may be considerably different from those obtained with spherical sliders. Hardy[(2)] studied binary mixtures of undecane and organic acids using spherical sliders and concluded, "Obviously the acid is condensed from the solution on to the surface so that save when less than about 0·7% is present the friction is the same as that for the pure acid." Our results with low pressures show finer differences; the μ-composition curves are more complex and resemble (in reverse) the shape of our curves for spreading [Fig. 2 (*a*)]. The friction results of Gauditz and Ramsauer[(3)] obtained using a plate bearing on rotating rollers are presumably boundary, but it has been possible to show correlation between these friction results and our spreading tests, with the same binary mixtures.

In Fig. 3 it is shown that a little engine oil added to iso-octane reduces the coefficient of friction at low pressure out of all proportion to the amount added. Included in the results are the rate of sedimentation and sediment volume of a suspension of carbon black in diluted engine oil.[(4)]

An analysis of the friction results of Gauditz and Ramsauer,[(3)] side by side with our spreading results, is given in Fig. 4. Corresponding to the decrease in friction with change of composition of the valeric acid mixture is the increase in rate and amount of spreading (and vice versa). Both the friction and spreading increases

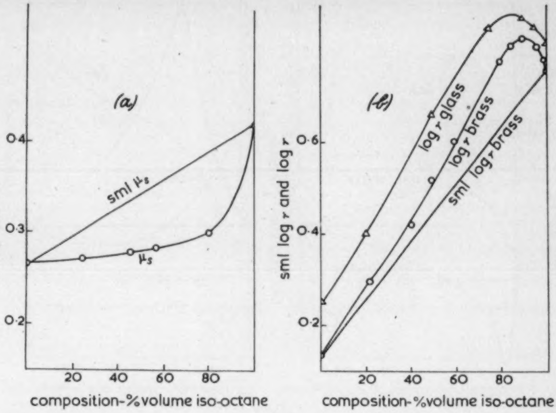


Fig. 1. Friction and spreading results for binary mixtures of a mineral engine oil with iso-octane: (*a*) Relation between composition and friction sml μ_s and μ_s; (*b*) relation between composition and spreading sml log r brass and log r brass and glass (for 1 ml after 1 000 sec)

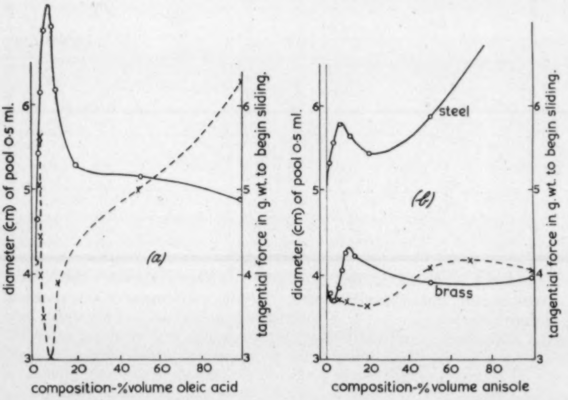


Fig. 2. Friction and spreading results for binary mixtures: (*a*) B.P. liquid paraffin and oleic acid: friction (chain line) glass/glass and spread on glass; (*b*) B.P. liquid paraffin and anisole friction: (chain line) brass/brass and spread on brass and steel

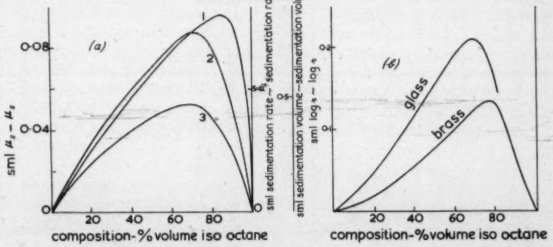


Fig. 3. The friction and spreading results for binary mixtures of a mineral engine oil with iso-octane: (*a*) (1) Relation between composition and friction sml $\mu_s \sim \mu_s$; (2) relation between composition and sml sedimentation rate ~ sedimentation rate (decrease) for carbon black (cm/sec); (3) relation between composition and sedimentation volume of carbon black (ml/g) ~ sedimentation volume (decrease). (*b*) Relation between composition and spread sml log $r \sim$ log r (increase) on glass and brass

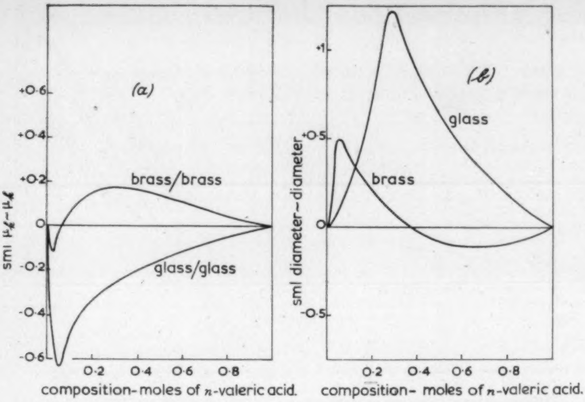
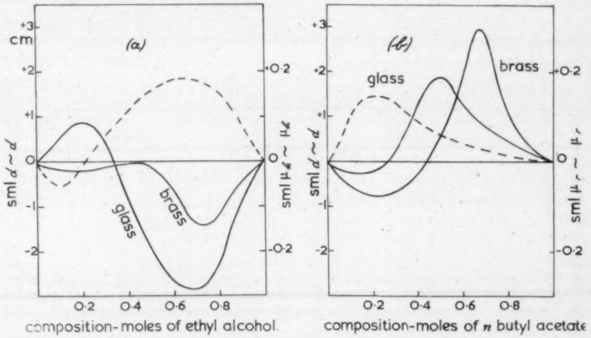


Fig. 4. Friction and spreading results for binary mixtures of cyclohexane and *n*-valeric acid. (*a*) Relation between composition and friction results after Gauditz and Ramsauer, sml $\mu_k \sim \mu_k$. (*b*) Relation between composition and spreading on glass and brass sml $d \sim d$, for 0·5 ml pool after 1 min

Fig. 5. Friction and spreading results, brass/brass, after Gauditz and Ramsauer for binary mixtures of cyclohexane with (*a*) ethyl alcohol and cyclohexane: spreading and friction (chain line); (*b*) *n*-butyl acetate and cyclohexane: spreading and friction (chain line)



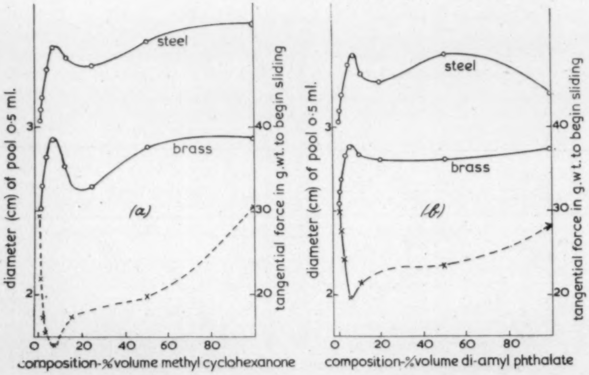


Fig. 6. Friction brass/steel (chain line) and spreading results for binary mixtures of B.P. liquid paraffin: (*a*) with methyl cyclohexanone; (*b*) with di-amyl phthalate

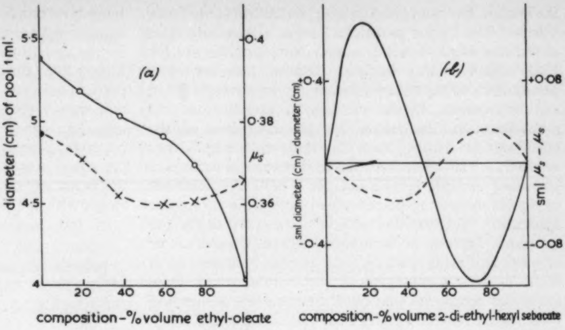


Fig. 7. Friction and spreading results for binary mixtures: (*a*) *n*-octyl alcohol and ethyl oleate: friction (chain line) steel/steel and spread over steel; (*b*) *n*-octyl alcohol and 2-di-ethyl-hexyl sebacate, friction (chain line) glass/glass sml $\mu_s \sim \mu_s$ and spread, sml diameter, $\sim$ diameter, glass

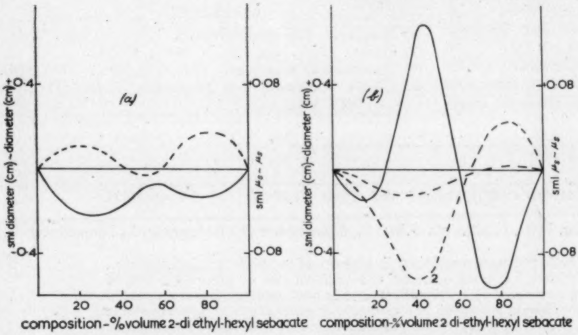


Fig. 8. Friction and spreading results for binary mixtures of *n*-octyl-alcohol with di-ethyl-hexyl sebacate: (*a*) friction (chain line) brass/brass sml $\mu_s \sim \mu_s$ and spread over brass sml $d \sim d$; (*b*) Friction (chain line) steel/steel (1) sml $\mu_s \sim \mu$: (2) sml $\mu_k - \mu_k$ (modified Wells machine) and spread over steel

are greater on glass than on brass. The results with the ethyl alcohol mixture are shown in Fig. 5(*a*), and for the butyl acetate mixture in Fig. 5(*b*), from which it will be seen that there is a fairly close correlation.

Passing from the low molecular weight hydrocarbon cyclohexane previously examined to the "non-polar" high molecular weight mineral oil the effect of adding a ketone, ester, acid and ether respectively was examined. The addition of small amounts of all four substances respectively to the liquid paraffin resulted in a substantial decrease in friction and a corresponding increase in rate and amount of spreading, the effect being similar on steel, glass, and brass. Beyond 10% additions there was a decrease in the effect, and it will be seen from Figs. 2 and 6 that the shapes of the friction-composition curves are almost mirror images of the spreading-composition curves on the various surfaces. Oleic acid had the greatest effect of the various additives, although the general shape of the curves is similar.

Tests with binary mixtures of *n*-octyl alcohol with 2 di-ethyl-hexyl sebacate and ethyl oleate, respectively, have given interesting results in that the highly specific effect of the chemical nature of the surface on the friction and spreading results is emphasized. Some results are shown in Figs. 7 and 8. On glass, the addition of the sebacate ester at first increases the spreading and reduces the friction, but when the equal volume mixture is reached there is a reversal of the effect. On brass, the spread decreases and friction increases and the same effect is obtained when the alcohol is added to the ester, the curves having a dumb-bell shape. On steel, the behaviour is more complex; the addition of the ester to the alcohol at first results in a small decrease in spreading, followed by a rapid increase with further additions, then at the compositions above equal volumes there is a rapid decrease in the spreading below the simple mixture law values. The friction results correspond closely; the initial decrease in spreading has its counterpart in a delay in the rate of decrease in friction with addition of the ester.

DISCUSSION

The reason why the addition in small quantities of "polar molecules" to a "non-polar" hydrocarbon lowers the friction has been given in great detail by Hardy(2) and others. The "polar molecules" form a boundary layer at the surface of the solid, so providing a carrier for the load of the sliding surface. Where, however, both constituents of the binary mixture are not strongly polar, as, for example, in the mixture of cyclohexane and *n*-butyl-acetate, the reason for the divergence of the coefficient of friction from the value calculated is not so clear. The close correlation between the rate of spreading and the lubricating action of binary mixtures of liquids appears to be related to changes in molecular association and resulting loss in surface activity of the mixture. This can be exemplified with mixtures such as of water and alcohol which form alcohol hydrates, or of acetic acid or *o*-chlor-phenol and aniline which form molecular complexes that have lower surface action and yield higher friction results than the constituents taken singly.

The connexion is more noticeable at low pressures when fluid friction predominates, but is not entirely lost at boundary load pressures. This is indicated by the friction results obtained by Gauditz and Ramsauer under boundary lubrication conditions. However, under boundary conditions in no case was the coefficient of friction with a mixture found to be lower than that given by the constituent with the better lubricating ability, nor higher than the coefficient of friction given by the constituent with the worse lubricating power. If the surface adhesion forces cause molecular fixation beyond the usual monomolecular layer it is probable that the mechanical resistance to shear decreases rapidly towards the liquid boundary of the adsorbed film, so the effective thickness of adsorbed film able to support the slider varies with the pressure.

ACKNOWLEDGMENT

Acknowledgment is made to the Chief Scientist, Ministry of Supply, for permission to publish this contribution to the Symposium.

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The electrostatic component of the force of friction

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Experimental evidence has been presented previously in support of the view that jerky motion ("stick-slip" motion) of a frictional contact operated at a uniform rate of propulsion was of electrostatic origin. The electrification of frictional contacts is now considered and illustrated by discharge currents made visible on the screen of a cathode-ray oscilloscope. With a metallic friction element loaded against a rotating steel disk rapid oscillations are obtained at linear speeds of several hundred centimetres per second. Their amplitude is independent of load and speed but can be increased by the addition of a dielectric material, and the oscillations can be made to disappear under conditions under which static charges cannot be held. Similar phenomena are obtained on substituting a rotating glass disk; then luminous spots are observed at temperatures below 400° C at the actual area of contact.

An elastically restrained "friction element" (i.e. a body which is in frictional contact) exhibits a series of jerks ("stick-slip" motion) when the other friction element is moved forward at a slow and uniform rate provided that the force of friction-velocity characteristic of the particular contact exhibits a non-linear falling section and a minimum.(1) Schnurmann and Warlow-Davies(2) suggested that for these relaxation oscillations of a frictional contact to occur the electrostatic force resisting displacement at the actual area of contact must assume an appreciable proportion of the force of friction, i.e. the force of friction must have an electrostatic component of a sensible order of magnitude when cycles of slow charging, followed by a rapid discharge, cause the elastically restrained friction element to move by a series of jerks. They presented experimental evidence to support this view. When the boundary layer of a frictional contact has dielectric properties, cycles of slow charging and rapid discharging cause relative motion to proceed by cycles of slow sliding and rapid slipping in the region of instability of the force-velocity characteristic of the frictional contact. With metallic friction elements and a boundary lubricant each jerk was shown to be accompanied by a deflexion of a ballistic galvanometer which was connected to the two friction elements until the rate of propulsion was chosen sufficiently large for the ballistic galvanometer to assume a steady deflexion because of its inability to resolve a rapid succession of cycles of charging and discharging.

Direct experimental evidence is now presented to show that at comparatively high speeds of relative motion (in the stable region of the force-velocity characteristic of the frictional contact) a cathode-ray oscilloscope to which one of the friction elements is connected indicates rapid oscillations and that these oscillations are of electrostatic origin.

ELECTRIFICATION OF FRICTIONAL CONTACTS

Contact electrification between two *naked* metal surfaces cannot make any contribution to the force of friction since the electric charges are mobile in the metal surfaces, so that no tangential component of the force of electrostatic attraction can arise while two pieces of metal free from any dielectric film remain in contact, though relative motion between them may take place.

The position is quite different when a dielectric material is sandwiched between the metal surfaces because then the position of the electrostatic charges is fixed on the surface of the dielectric. In these circumstances the value of the contact potential oscillates during relative motion between the static value and the limit at which the dielectric breakdown field strength of the thin film of insulating material is reached,[3] since, as indicated in Fig. 1, it is assumed that each complete discharge is followed by the almost instantaneous establishment of the static value of the contact potential. The frequency of the oscillations is governed by the rate of charging from the static to the limiting value, and this rate in turn is determined by the rate of propulsion of the friction element which is moved forward uniformly, so that the frequency of the electrical oscillations increases with the average speed of relative motion.

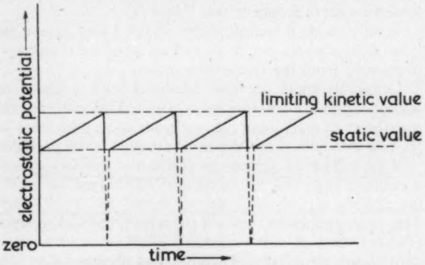

Fig. 1. Schematic representation of the oscillations of the electrostatic potential in friction

EFFECT OF DIELECTRIC PROPERTIES OF BOUNDARY LAYER

If the electrostatic interpretation of jerky motion is correct, it follows that the electrical oscillations must occur in increasingly rapid succession with an increase in the average velocity of relative motion between the friction elements, even in the stable region of the force-velocity characteristic of the contact where the force of friction grows with increasing velocity of relative motion. In this region of rapid succession of cycles of charging and discharging, the inertia of the restrained friction element is responsible for its continuous motion and thus for the stability of the mechanical conditions. A cathode-ray oscilloscope connected to a constantan friction element which is loaded against a flywheel of steel, as illustrated in Fig. 2, resolves the electrical oscillations at a speed of relative motion of the order of 400 cm/sec. The interesting point for the interpretation of the oscillations made visible on the cathode-ray screen is that on applying to this "dry" contact a mineral oil (medicinal liquid paraffin, for instance) the amplitudes of the oscillations on the cathode-ray screen increase appreciably (Table 1). This is regarded as direct evidence that these oscillations indicate electric discharge currents, and it is in keeping with this interpretation that the amplitudes are independent of the speed and of the normal load in contradistinction to any thermal electromotive force on account of the frictional heat which at a given normal load grows with the speed and at a given speed increases with the normal load.

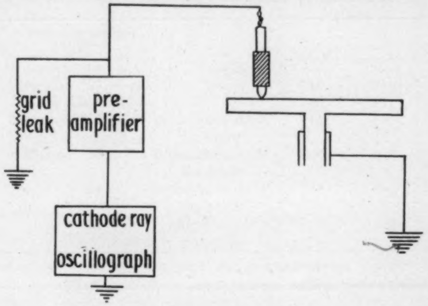

Fig. 2. Block diagram of the electrical circuit used in the experiments

Table 1. *Amplitudes of oscillations on cathode-ray tube screen for frictional contact of constantan on steel*

Lubricant	*Normal load lb-wt.*	*Linear speed cm/sec*	*Amplitude of oscillations in millivolts*	
			Mainly	*Occasionally*
No lubricant	0·5	410	± 1	± 2·2
No lubricant	1·5	410	± 0·6	± 1 (very few)
No lubricant	3·0	410	± 0·5	± 0·6 (a few)
No lubricant	0·5	410	± 0·7	± 1
No lubricant	0·5	517	± 0·7	± 1·2
No lubricant	1·5	517	± 0·7	± 0·9
Medicinal liquid paraffin	0·5	517	+ 2 (some of + 4·8) − 1 (average)	
Medicinal liquid paraffin	1·5	517	+ 3·6 − 1 (average)	
Medicinal liquid paraffin	3·0	517	+ 3 − 1 (average)	

In all these measurements (Tables 1, 2 and 5) the resistance of the grid leak of the preamplifier was 250 000 Ω.

Large amplitudes can be obtained with a thin mineral oil of good wetting power, and the experiments summarized in Table 2 show the sensitivity of the oscillations to the maintenance of the oil supply to the friction track. The amplitudes can be increased by maintaining an oil feed to the steel plate, and they decrease again on stopping this oil supply.

Another simple demonstration of the electrostatic nature of the oscillations which are made visible on the cathode-ray screen is that these oscillations can be made to disappear by breathing on the steel plate.

Table 2. *Effect of maintenance of supply of a thin oil film on amplitudes of oscillation (frictional contact: constantan on steel)*

Normal load lb-wt.	*Speed cm/sec*	*Oil supply*	*Amplitude of oscillations in millivolts*	
			Mainly (upwards)	*Average (downwards)*
0·5	517		>+ 12*	− 4·2
1·5	517		+ 6·6	− 3
1·5	517	With addition of more oil	>+ 12*	− 4·8
3·0	517	With addition of more oil	+ 16	− 6
0·5	517	With addition of more oil	+ 42	− 6
0·5	517	On stopping oil supply	+ 18	

* These figures indicate full scale readings for a particular amplification range.

LUMINOUS SPOTS AS INDICATIONS OF ELECTRIC DISCHARGES

Bowden, Stone and Tudor(4) were the first to describe the observation of luminous spots when loading a metallic friction element against a rotating glass disk and viewing the contact area through the glass plate. The interpretation of these luminous spots as the indications of electric discharges can be supported by five simple experiments. In the first place, the temperature can be measured at the actual area of contact when these scintillations are observed. For this purpose the "hot" junction of a thermocouple serves as the metallic friction element which is loaded against the glass disk. Since one has to consider that a "hot" junction reads lower when loaded against a flat surface than when embedded in the "hot" medium, the difference between these two values was determined separately when one of two similar "hot" junctions was embedded in a heated metal plate and the other loaded against the stationary plate at a series of normal loads. With this empirical correction it was found that the luminous spots appeared at temperatures below 400° C (Table 3).

Secondly, for the observation of luminous spots and of oscillations on the cathode-ray screen it is essential for the metallic friction element to tear a track on the glass plate so that it does not run on a film of metal smeared on to the glass plate. This is borne out by the observations recorded in Table 4. This table shows that the appearance of luminous spots was not connected with a definite minimum temperature at the actual area of contact, since without tearing of the glass plate a temperature of 356° C could be reached and still no luminous spots were observed, whereas when tearing took place pin-point luminous spots were observed at 147° C.

Thirdly, the amplitudes of the oscillations on the cathode-ray screen can be increased by rubbing the glass plate with a piece of cotton wool, whereas breathing on the glass plate tends to annihilate the oscillations.

Fourthly, intermittent application of a mineral oil to the track on the glass disk, while quenching the luminous spots which are the indications of an electric discharge through a thin film of air, does not remove the oscillations on the cathode-ray screen but it results in a larger normal load being required after removal of the oil to make the luminous spots reappear (see Table 3).

Finally, with a metal probe about 1 mm above the glass disk, charges can be picked up from the disk where it emerges from the frictional contact.

Luminous spots are also observed with a glass rod loaded against a rotating glass disk. This excludes the possibility of explaining the luminous spots with metallic friction elements as pyrophorous abraded metal particles.

With a friction element of constantan loaded against a rotating steel disk an increase of the amplitude of the oscillations on the cathode-ray screen has been found with the application of oil to the frictional contact (Table 1) and the corresponding effect of maintaining a continuous oil supply (Table 2) was shown. On substituting a glass disk, which by itself is a better dielectric than an oil, the observation was made (Table 5) that the application of oil to the actual friction track by means of a dropping funnel adjacent to the metallic friction element diminishes the amplitudes of the oscillations, and pouring of oil on the disk causes a still larger decrease.

CONCLUSION

Experimental evidence is presented of electric discharge currents accompanying relative motion between metallic friction elements at linear speeds of the order of several hundred centimetres per second. The application of an oil to the frictional contact significantly increases the amplitudes of the oscillations registered by a cathode-ray oscilloscope. On the other hand, breathing on one of the friction elements (a metal disk) tends to annihilate the oscillations indicated by the cathode-ray screen, since static charges cannot be held on the surface of the disk under these conditions.

On substituting a glass plate for the metal disk, luminous spots are observed at the area of the frictional contact. In accordance with the electrical interpretation of these scintillations the temperatures at the area of the frictional contact are determined to lie below 400° C. The scintillations are accompanied by oscillations on the

Table 3. *Temperature at actual area of contact ("hot" junction of thermocouple loaded against rotating glass disk) when luminous spots are observed*

Lubricant	*Normal load lb-wt.*	*Linear speed cm/sec*	*Calibrated temperature °C*	*Luminous spots*	*Remarks*
None	1·5	336	231	Very small and faint	Noise from tearing of track on glass plate
None	1·5	380	266	Faint	Loud noise
None	1·5	518	369	Bright	Loud noise
Medicinal liquid paraffin	2·0	350	63	None	The temperature tended to rise gradually unless sufficient liquid paraffin was supplied to the contact
Medicinal liquid paraffin	4·0	350	63	None	
Medicinal liquid paraffin removed	3·5	429	262	None	
Medicinal liquid paraffin removed	4·5	429	273	Visible for short periods	
Medicinal liquid paraffin removed	5·0	429	323	Just visible	
Medicinal liquid paraffin applied for second time and removed again	5·0	429	216	None	
	6·0	429	260	None	
	6·5	429	292	Visible but dull red	
	—	—	354	Visible	

Table 4. *Data showing the importance of tearing a track on a glass plate for obtaining luminous spots*

"Hot" junction of thermocouple	*Normal load lb-wt.*	*Linear speed cm/sec*	*Calibrated temperature °C*	*Luminous spots*	*Remarks*
New junction, end filed fairly flat	2·5	407	335	None	Starting new track on glass plate
New junction, end filed fairly flat	3·0	407	330	None	
New junction, end filed fairly flat	3·5	407	356	None	
New junction, end filed fairly flat	1·5	407	399	Just visible	Tearing of glass plate
New junction, end filed fairly flat	1·5	336	232	Visible	
New junction, end filed fairly flat	1·5	380	266	Faint	
New junction, end filed fairly flat	1·5	518	369	Bright	
New junction, end filed fairly flat	1·0	448	147	Small pin points	
End worn	5·0	429	321	Just visible	
End worn	5·5	429	121	None	Cleaning glass plate with cotton wool after application of medicinal liquid paraffin

Table 5. *Effect of maintenance of supply of oil on amplitudes of oscillations on cathode-ray screen (frictional contact: constantan on glass)*

Lubricant	*Method of oil supply*	*Normal load lb-wt.*	*Linear speed cm/sec*	*Amplitude of oscillations in millivolts*	
				Mainly	*Occasionally*
None	—	0·5	517	± 2	± 4
None	—	1·5	517	± 4·8	± 9
Medicinal liquid paraffin	Dropping funnel	1·5	517	± 2	± 4
Medicinal liquid paraffin	Pouring on disk	1·5	517	± 0·6	± 0·8
Medicinal liquid paraffin	Dropping funnel	3·0	517	± 2	± (3 to 4)
Medicinal liquid paraffin	Pouring on disk	3·0	517	± 1	± 1·8
Medicinal liquid paraffin	Dropping funnel	0·5	410	± 0·8	± 1·1
Medicinal liquid paraffin	Dropping funnel	1·5	410	± 1·8	± 2·8
Medicinal liquid paraffin	More oil poured on	1·5	410	± 2	± 2·4
Medicinal liquid paraffin	Dropping funnel	3·0	410	± 2·4	± 4
Medicinal liquid paraffin	More oil poured on	3·0	410	± 1·2	± 2

cathode-ray screen. These oscillations must be the indication of the electric discharge currents flowing through the grid leak of the preamplifier of the cathode-ray oscilloscope. Rubbing the glass plate with cotton wool increases the amplitude of the oscillations, whereas breathing on the glass plate annihilates them. A metal probe set up behind the frictional contact and about 1 mm above the glass disk picks up static charges from the frictional contact.

These results are regarded as corroborating previous consideration(2) of the electrostatic component of the force of friction of which there is some indirect evidence in the work of Wells(5) and which is claimed to be responsible for some wear results recorded by Kyropoulos.(6)

ACKNOWLEDGMENTS

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DISCUSSION

Dr. F. T. Barwell: Dr. Schnurmann has stated that the temperatures recorded by the thermocouple when used as a rubbing contact did not exceed 400° C. In view of the extremely short duration of the temperature flashes, has he corrected his results for the thermal capacity of the hot junction, or does he think that the true temperature of the rubbed surface might have momentarily exceeded the values quoted?

Dr. J. S. Courtney-Pratt: Dr. Schnurmann has advanced a theory of friction, and has endeavoured to explain most of the phenomena in terms of electrostatic charges. Electrostatic phenomena have been known for very many years, and the demonstrations he has given have merely shown that charges can be produced. There is no real evidence from these experiments that the electrostatic forces form any significant part of the forces of friction. Between metals, in fact, the work involved in overcoming friction is many thousand times larger than the work of separating charges, even when they are as large as the speaker himself claims. We have made measurements in our laboratory and find with metals at appreciable loads that the electrostatic component is quite insignificant. Even in a favourable case it amounted to no more than 5 mg when the total friction was a kilogram. In the friction of non-conductors such as silk or cotton fibres *under light load* the electrostatic attraction may of course be a larger proportion.

It is common knowledge that when two materials are rubbed together, heat is generated. Bowden and Ridler(1) used various metal pairs and measured the thermo-electric voltage so that they could find quantitatively the mean temperature to which the surfaces were raised. This work has been extended by a number of workers since then.

Dr. Schnurmann has suggested that the thermo-electric voltages were, in fact, electrostatic potentials. It is surprising, then, that the sign of the potential is always that which would be predicted from the position of the metal pair in the thermo-electric series, and that it does not show the vagaries of sign and magnitude that are always associated with electrostatic potentials.

When two materials are rubbed together, the highest temperature that is likely to be reached is the melting-point of the more fusible of the two materials. The thermo-electric potentials do show that temperatures up to this maximum can quite easily occur, and that temperatures above this are not recorded. It would again be surprising if the electrostatic phenomena should fortuitously show such a consistency.

Dr. Schnurmann and others have suggested that it is unlikely that temperatures as high for example as the melting point of steel should occur when the conditions of rubbing are not very severe. They suggested that the conductivity of the metals would prevent such high temperatures being reached. The thermal equations have been formulated and studied in detail by P. H. Thomas(2) and the work reviewed by Professor Christopherson. Briefly, if heat is applied to a small area on the surface even of a semi-infinite solid with a conductivity as high as that of a metal, the temperature gradient can be so steep that the region of application of heat can be raised many hundreds of degrees above the temperature a short distance away. We suggest that the area over which the frictional work is lost, and over which the heat is applied, is the area of real contact which is given approximately by the ratio of the normal load and the flow pressure of the material under the conditions of operation. The experimental work on the reality of this area of contact is amply demonstrated by the work of Ragnar Holm[(3)] and of Bowden and Tabor.[(4)] The predictions from the thermal equations have been extensively tested by experiment, and the confirmation is extraordinarily close. Increase of frictional work increases the temperature: decrease of thermal conductivity will increase the temperature, and temperature of 1 000° C can be produced with a normal load of a kilogram and a sliding speed of 100 cm/sec. The apparent area of the bearing face is not relevant as the real area of contact is independent of the apparent area.

Parker and Marshall[(5)] measured the temperatures of railway wheels. They found temperatures of several hundred degrees, though still considerably lower than those that we measured; but they measured the average temperature over an area about a quarter of an inch across, and they measured this temperature some time after that part of the rim of the wheel had appeared from under the brake-block. That is, they measured the temperature at least a millisecond after the application of the heat. In certain of our experiments we used one surface of transparent material and studied the surface through this transparent rotating disk.[(2, 4, 6)] We found that the duration of the hot spots was usually very short. The temperature flashes often occurred and decayed again within times of the order of fifty or a hundred microseconds, so that temperatures measured a millisecond late would obviously be much lower than the peak temperatures. The size of the hot spots was comparable with the regions of real contact area as would be expected, and their apparent colour temperature increased as the thermal equations would predict with increase of speed, load, etc.

Dr. Schnurmann has suggested that these visible hot spots were electrostatic discharges. Were this so, the light output should be related to the discharge spectrum in air. It would not exhibit the colour temperature changes that we observe. To confirm this further, Thomas used both visible-light and infra-red photocells for quantitative determination, and fitted chopper disks with alternate segments of an infra-red absorbing filter. By means of these he could measure the mean and peak temperatures of the hot spots over the whole range from 200° C up to 1 000° C or more.

Further evidence of the reality of the temperatures has been obtained using a series of alloys of gold and silver that have almost constant thermal and physical properties, but with a range of melting points. If the melting point is below 500° C red hot spots are not visible. The lead sulphide cell shows temperatures up to the melting point. If the melting point is above this, then red hot spots are visible. In another experiment the surfaces were lubricated with an explosive that would detonate if heated to a temperature of 500° C. As predicted, the explosive could be ignited if the melting point of the slider were above its ignition temperature.

In view of the weight of this evidence, there can be no reasonable doubt that these high temperatures do often occur in quite mild conditions of sliding, and these phenomena of friction may better be interpreted in terms of the bulk physical properties of the material, with due regard to the change of these properties at the temperatures obtaining at the points of contact.

Mr. A. J. Chisholm: There are presumably numerous isolated points at which contact is established simultaneously between two sliding surfaces, and the temperatures at these points will differ widely. A thermocouple rubbing on a moving surface as in the experiment described by Dr. Schnurmann—even if the thermocouple has a negligible heat capacity—would not therefore record the maximum temperature attained at the interface, but a mean value. In view of this, does Dr. Schnurmann think that the temperature of 400° C mentioned by him refers to the temperature of the "hot spots" which first appear as the speed or load is increased? It seems rather that the measured temperature should be appreciably lower than the actual temperature of the hottest of the points of contact between the surfaces.

Similarly, when use is made of the actual sliding surfaces to form a thermojunction to measure the interface temperature, it would be expected that the recorded temperature would thus be considerably lower than the peak value attained on the surface at a particular instant.

Mr. J. E. Stringer: Dr. Schnurmann states that the vertical flashes shown on the cathode-ray oscilloscope attached to the glass disk friction-apparatus are due to the build-up of electric charges at the point of rubbing, but others suggest the flashes are due to thermo-electric effects due to heat of rubbing.

To prove this point perhaps a test run could be made with castor oil, which has an SIC of approximately 5·6 as compared with approximately 2·3 for mineral oil; if the voltage build-up were a function of the oil, it would seem reasonable to expect bigger flashes using the castor oil. Dr. Schnurmann said he would expect smaller flashes because the breakdown voltage was smaller.

The lecturer (amid cheers) tried some castor oil supplied by Mr. Stringer but the flashes were smaller. In order not to take up too much of the available discussion time, the matter was not taken further.

Author's reply: In reply to Dr. Barwell there would seem to be little reason to suppose that the true temperature of the rubbed surface might have momentarily exceeded the measured values. One piece of experimental evidence is that the indicating instrument to which the "hot" junction of the thermocouple forming one of the friction elements was connected should show a continuous deflexion instead of oscillations if the luminous spots were an indication of temperature radiation and not of electric discharges. Although during one run the location of the luminous spots on the nominal area of contact might change, the high thermal conductivity of metals would not allow of any appreciable temperature gradient over a short distance through the bulk of the metal. This is one of the fundamental differences between a thermal insulator and a metallic conductor. It is everyday experience that a cigarette with its appreciable proportion of air spaces between the parts of the shredded tobacco leaf can be held comfortably very close to its burning end, whereas it would be impossible to hold with impunity with one's bare fingers a metal rod of ¼ in diameter near to its red-hot end.

Some apparent misunderstandings in the arguments presented by Dr. Courtney-Pratt seem to require sorting out. The point was made in the paper that the contact potential between *naked* metal surfaces would make no contribution to the force of friction and that for an electrostatic component of the force of friction to arise the fixing of the positions of static charges on at least one of the surfaces is required, in the case of metallic friction elements by means of a thin film of contaminating dielectric material, for instance. There is general agreement that when two materials are rubbed together heat is generated. Dr. Courtney-Pratt mentions that when two materials are rubbed together the highest temperature that is likely to be reached is the melting point of the more fusible of the two materials, and he refers to Bowden and Ridler's experiments. Dr. Courtney-Pratt thinks that the thermoelectric potentials do show that temperatures up to this maximum can quite easily occur. Bowden and Ridler's experiments show, in fact, that the temperatures attained at the actual area of contact depend on the magnitude of the frictional force and the speed of relative motion between the two friction elements and on their thermal diffusivities. Thus, for gallium on steel at 17° C Bowden and Ridler found that at a normal load of 27 g-wt the high speed of relative motion of 720 cm/sec was required to achieve a temperature rise at the actual area of contact by 13·2° C, i.e. a rise from 17° C to 30·2° C, which is the melting point of gallium. It appears very unlikely from this that temperatures as high, for example, as the melting point of steel should occur when the conditions of rubbing are not such that the normal load assumes high values and also the speed of relative motion. This again is experimentally borne out by Bowden and Ridler's experiments, who for lead on mild steel required a load of 101 g-wt at a speed of relative motion of 485 cm/sec to reach *at the actual area of contact* the melting point of lead (327·4° C), and who for the comparatively poor thermal conductor Constantan on steel were unable to come anywhere near the melting point of Constantan (1 280° C) at normal loads of 100 g-wt and at speeds reaching 1 100 cm/sec.

It is not clear where Dr. Courtney-Pratt finds justification for his statement that I had suggested that the thermoelectric voltages were in fact electrostatic potentials.

The Ph.D. thesis of P. H. Thomas(2) is not known to me, and it will be interesting to have an opportunity of seeing under what conditions for a semi-infinite solid with a conductivity as high as that of a metal "the temperature gradient can be so steep that the region of application of heat can be raised many hundreds of degrees above the temperature a short distance away."

The experiments using a series of alloys of gold and silver with a range of melting points are not necessarily evidence of the reality of temperature radiation as the explanation of luminous spots, since it may well be that under mild conditions of frictional contact these soft alloys are wiped out on the glass surface and provide at the actual area of contact virgin metal faces so that no appreciable charge separation could take place and that for this reason no luminous spots are observed.

As far as my paper is concerned, Dr. Courtney-Pratt may have overlooked that one of the experiments showed a distinct increase of the amplitudes of the oscillations demonstrated on the screen of a cathode-ray oscilloscope when some mineral oil was added to a frictional contact which consisted of a metallic friction element that was loaded against a rotating metal disk. Another of the experiments showed that breathing on the metal disk annihilated the oscillations on the cathode-ray screen.

The question raised by Mr. Chisholm would again appear to hinge on the still debatable point whether an appreciable temperature gradient exceeding the value compatible with the bulk thermal conductivity of metals can be attained at a metal surface.

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Physical changes in rubbing surfaces on scuffing

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Cast-iron surfaces rubbing against steel have been found to develop a thin layer of a "white constituent" when scuffing occurs or is approached. This material has not been fully identified, but the results point to it having a basis of two phases, viz. cementite and a quenched high-carbon ferritic phase developed from austenite, resulting from the high temperature developed by rubbing. In the laboratory work, using a 4-ball apparatus modified to take piston ring segments, this white material was also obtained in some degree with mineral oil under milder conditions than those causing scuffing, but not with the castor oil which proved better in preventing scuffing in running-in an aero-engine.

The work was carried out early in the war period and was not completed. These particular results, and a number of others, are recorded to draw attention to this phenomenon, which has also been noticed in the U.S.A., and may act also as pointers to the further work that should be carried out to elucidate the phenomena associated with the running-in of surfaces and scuffing.

The basis of this paper is a collection of results, obtained in 1941, of the microscopic examination of the physical condition of surfaces after scuffing or approach to it. The investigation was not completed, but the results are thought to be sufficiently interesting to encourage further work on these lines when investigating scuffing and seizure of surfaces. The observations showed the development of increasing amounts of a white constituent in the surface layer as scuffing was approached with a mineral oil. Observations of a similar kind were made in the U.S.A. later in the war, as mentioned in more detail below, but there is little evidence in this country of further work on these lines being done. It is thought worth while to outline the main results obtained at the National Physical Laboratory, partly to draw attention to the phenomenon in itself but also because, in the absence of a convenient method of measuring the surface temperature and, sometimes, of notable changes of friction value, it would appear that the development of the white constituent is a first indication of unsuitable conditions and perhaps impending failure.

Application of the observations to gear surfaces and to piston rings is most obvious in practice; but there may be useful observations to be made in other cases of quick sliding either in the fabrication of metals or in the service of components. The phenomena depend on both the rubbing surfaces and the lubricant, and useful deductions on the quality of either are possible.

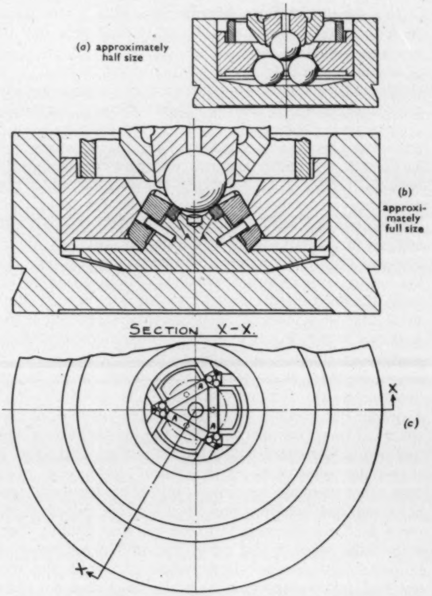

Fig. 1. Four-ball lubricant testing apparatus and modification for testing piston ring segments. (Diameter of ball ½ in)

The work described was a continuation of an established programme of investigation of the scuffing of surfaces at the National Physical Laboratory. A particular bias was introduced at the time from practical difficulties experienced in running-in a particular type of new aero-engine; scuffing of the cast-iron piston rings (i.e. tearing of the surface) occurred with mineral oils and satisfactory freedom from it could be obtained only with castor oil; this position was intolerable under war conditions on account of the additional work involved in cleaning out the castor oil, necessitated by its relative immiscibility with the mineral oil to be put in subsequently and by the deterioration of the engine that

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would occur in storage before use. No adequate apparatus was available to imitate the aero-engine conditions, and so some tests were carried out in the 4-ball apparatus to see whether any observations could be made which might throw light qualitatively on the problem, and suggest lines of trial, pending the construction of a reciprocation apparatus using actual cylinder liner strips and piston ring segments. Some corresponding features were noted, as mentioned below, but the work on the engine was stopped before the present research had reached a practical stage, and the laboratory work itself had to be suspended a little later. The results are therefore reported for their general interest.

APPARATUS AND METHOD OF TEST

The 4-ball lubricant testing apparatus[1] was used. In its normal form a $\frac{1}{2}$ in diameter hard-steel ball of usual manufacture from a high carbon chromium steel is rotated under load in the cavity formed between three similar balls clamped together in a cup containing the lubricant, as shown in Fig. 1(*a*). Circular wear impressions are formed on the three stationary balls, and a wear ring on the rotating one. The circular impressions are small if scuffing has not occurred, being slightly enlarged from the Hertz elastic deformation under the particular load (about 0·01 in diameter for 20 kg load on the rotating ball). If, however, scuffing occurs the circular impressions are much larger and rougher (about 10 times the diameter for scuffing with mineral oil). In the experiments reported, portions of piston ring in the form of segments (form cast to Air Ministry Specification DTD 413) were substituted for the three stationary balls, as shown at *A* in Fig. 1(*b*) and (*c*); this arrangement gave continuous rubbing of the piston ring surface, as occurs in an engine. With the ring segments rather larger impressions were formed than with balls, partly owing to a nearly flat surface being substituted for one of the spherical ones, but also because the elastic limit of the cast iron is so much lower than that of hard steel. Fig. 2 shows the appearance of the "wear" impression on a ring after running for 1 min at 190 kg (load on top ball) without scuffing occurring. With piston rings much higher loads were required to cause scuffing than with balls; when it did occur the amount of material removed was so much larger than with balls that the test had to be stopped at an early stage, and not continued for the 1 min usual in tests with balls. Scuffing of piston rings occurred at about 250 kg with mineral oil and some tests were made near this load, some giving scuffing and some not. Scuffing of steel balls for the same lubricants occurred at about 60 kg; at 250 kg balls would not merely scuff but would weld solidly together. The coefficient of friction during scuffing was never so high with cast-iron rings as with steel balls.

ORIGINAL OBSERVATIONS

The white constituent in the micro-structure of the wear impressions was first observed when the structure of the worn surface of a laboratory test specimen was examined to see whether there was any evidence of change due to rubbing. Highly reflecting portions of the torn surface were noticed, due to the presence of a "white constituent," not readily identifiable, which was streaked in the direction of the rubbing motion and was obviously connected with the wear process (Fig. 3). As this constituent might be significant, further tests were made. Also some piston rings from the aero-engine referred to were examined. The following account is based on a selection of the many photo-micrographs taken, both of piston rings and of steel balls tested for comparison. All the surfaces were lightly polished before photographing. The specimens were all etched in a dilute solution of nitric acid in alcohol except where otherwise stated.

Figs. 4, 5 and 6 show the surface structures of three typical piston rings after running-in in aero engines. That in Fig. 4 had "seized" in the engine and the surface is seen to be almost covered by the layer of white constituent; also there is considerable cracking of this layer. Fig. 5 shows the surface of a "feathered" ring (some scuffing and surface flow of metal) which represents unsatisfactory running-in; the surface has considerable amounts of white constituent in it. Fig. 6 shows the surface of a ring which had run-in satisfactorily using castor oil; no white constituent is present.

Fig. 7 is the wear impression of a ring segment tested in the modified 4-ball apparatus at 60 kg for 20 min with plain aero-engine mineral oil to the old DTD 109 specification (S.A.E. 50 viscosity grade), no scuffing having occurred. A moderate amount of white constituent has formed; some of this is also shown by Fig. 8 at higher magnification. (The black marks on one corner of Fig. 7 are the remains of the circumferential machining marks on the working face of the new ring.) Figs. 9 and 10 show the absence of white constituent when castor oil, which was so good in running-in the aero-engine, was used at the same load; also the cast-iron structure is undistorted. Fig. 11 shows a portion of the track on the rotating ball: again there is no sign of the white constituent.

At the increased load of 250 kg (which is the load at which scuffing may occur), Fig. 12 shows the surface of the wear cavity in the piston ring segment at high magnification (comparable with Fig. 8), and Fig. 13 the edge of the track on the ball, after 1 min with plain mineral oil; a considerably greater amount of white constituent had formed on the ring segment than at the lower load in a longer time, but not very much on the ball. On the other hand, if scuffing did occur at this load, the ring surface took on the appearance shown in Fig. 14, where not only was there much white constituent but it was badly cracked, and, as the portions out of focus show, the flakes of material were distorted; this was similar to the condition of the piston ring heavily scuffed in the engine (Fig. 4). A more continuous white constituent layer than that in Fig. 12 is shown in Fig. 15, the edge of the impression on another ring, run at 220 kg with plain mineral oil for 1 min, without scuffing. In the comparison of Figs. 12 and 15 it is to be noted that the ring used for the former was as machined while for the latter it was treated by an etching method in nitric acid to remove some of the ferrite from the surface. It is of further interest that, with partial removal of the surface by long polishing with fine alumina, the kind of continuous white constituent in Fig. 15 gave place to streaks following the direction of rubbing; Fig. 16 shows this effect, the white constituent occupying the scores across the surface, where the working has been greatest. When scuffing occurred with four balls, white constituent was produced in plenty, e.g. Fig. 17 for plain mineral oil at 75 kg, run for 1 min.

INTERPRETATION

It appeared, therefore, that the white constituent could be produced freely with mineral oil when high loads caused scuffing or when the scuffing load was approached. It could also develop in lower-load/longer-time runs. Although neither loading condition could be claimed to represent closely the circumstances of running-in piston rings, it was considered that the lower-load/longer-time running was the more significant, and the correspondence of behaviour with mineral oil and castor oil in the laboratory test under these conditions with that in the engine in respect of white constituent formation was certainly interesting. In any case the formation of a seemingly new product or products in the microstructure was noteworthy.

A number of experiments was made to try to identify the white constituent. Etching reagents had shown it not to be martensite, but it etched in hot sodium picrate solutions in a similar manner to iron carbide; the other evidence, however, did not fit in with the material being at any rate wholly carbide. When a test piece similar to Fig. 15 was tempered at 650° C for 2 h there was a small proportion of a darkly etching constituent which was similar in appearance to heavily tempered martensite, but there was still much white material present, which seemed likely to be carbide. These features were consistent with the ring having been etched in nitric acid before use to eliminate much of the ferrite from the surface structure. Again when a section of the layer on the top ball shown in Fig. 17 (4-ball test, with scuffing) was examined there was a layer of white material on the surface and a band of martensite underneath. Moderate temperature heat-treatment had no effect, but with 2 h at 550° C the white material developed a structure similar to tempered martensite. This pointed to the predominance of material that had been austenite at the high temperature of rubbing; not much carbide was present. White constituent was not prominent in tests with ball on ball when no scuffing had occurred even though there had been much deformation of the surface.

Considering the influence of carbon on the formation of white constituent, the amount of the latter obtained was greater with the high carbon content rings (3·4% total carbon), and particularly when some ferrite had been removed by etching, than with the 1·2% carbon balls. The latter seemingly formed white constituent only with the high temperatures generated in scuffing, whereas the rings could form it freely at loads just below those causing scuffing, and to some extent by local action at much lower loads with mineral oil; under the low load conditions no white constituent was formed with castor oil, probably due to local temperatures not being sufficiently high and possibly to rapid wear of the ring material at high spots (see later). It appeared that the mineral oil, although largely carbon, did not provide a source of carbon as easily available as the graphite in the rings even at the high temperatures of rubbing. (Carbon enters austenite readily above 900° C, but below this temperature only slowly enters ferrite.) There was some confirmation of this position in an experiment with a carburized pure iron (thus avoiding any complication due to the phosphide eutectic present in the cast-iron piston ring); it was prepared by treatment for 8 h at 927° C in a powdered carburizing mixture and subsequently normalizing at 950° C in a vacuum to bring the carbon (somewhat over 0·9%) wholly into the form of iron carbide (Fig. 18). Testing rectangular specimens in the same way as the piston ring segments in Figs. 12 and 15 no white constituent was formed in the (non-scuffing) run with plain mineral oil. However, with a concentrated colloidal graphite mixture (2% graphite in oil) instead of plain oil, scuffing occurred at the same load and the test had to be stopped quickly; there was a heavy layer of white constituent on both the test pieces and the ball, a striking feature being the chatter marks in the white layer (Fig. 19). The external graphite coupled with the high temperature of scuffing had resulted in the formation of the white material.

Direct examination by X-rays of the surfaces in Figs. 12 and 15 failed to indicate the nature of the material at the surface, possibly because of the limitation introduced by the thinness of the layer (10^{-4} or 10^{-5} in) in relation to the depth of penetration of the X-rays. As it appeared that a high rate of quenching was probably involved, a very rapidly quenched specimen was prepared using the same carburized pure iron mentioned above. The specimen ($\frac{3}{8} \times \frac{3}{16} \times \frac{3}{16}$ in) was heated in a vacuum to 1100° C and after 15 min at that temperature was quenched in iced water. When a face of the specimen was polished and etched, one corner proved to be resistant to the usual etching reagents except hot sodium picrate solution. This suggested that this corner was more rapidly quenched than the remainder. An X-ray diffraction photograph from this corner, with glancing angle technique showed the presence of some retained austenite and a larger proportion of a constituent similar in crystal structure to α-iron. The tetragonal martensite structure was not present (an unexpected result). Moving towards the centre of the face the normal structure of a rapidly quenched steel (i.e. tetragonal martensite with some austenite) was found. In this region also the surface consisted in part of etching and in part of non-etching areas.

This simple quenching test suggests that as a result of extreme quenching speeds on carbon steels in the austenitic range at high temperatures unusual conditions are created, and it is of interest that the products are resistant to etching in a similar manner to the white constituent observed in the scuffing test. More work is required to confirm these preliminary observations and to find out whether a definite relationship exists between the products of extreme quenching and the white constituent.

There is some evidence from these experiments to indicate that at the temperature of formation (due to scuffing or approach to it) the white constituent consists of two phases: these would appear to be cementite and austenite, the proportion of each depending on the composition of the rubbing materials and in particular on the amount of carbon available. Normally the austenite would form martensite, but it is tentatively suggested that for some reason it forms a constituent similar to α-iron which would be supersaturated with carbon; it etches with hot sodium picrate solution. Possibly the extremely rapid quench and/or the association of free cementite in excess of that required to saturate the austenite at the temperature of formation might help to bring this about. Insufficient experimental work has been carried out to account fully for the phenomena associated with the formation and tempering of this material closely similar to α-iron.

DISCUSSION OF OTHER WORK

Since the experimental work described above was carried out, records of researches have been published in the U.S.A. which are of considerable interest. B. W. Sakmann[2] refers to the metallurgical transformations which occur on the rubbing of hardened surfaces and notes the etching characteristics and physical properties of the transformed material. Some of his conclusions seem to be similar to those of the present investigation. The work pointed to the formation of a carbide-rich phase at locally high temperatures and these could be high enough to cause decomposition of the lubricants, giving rise to nascent carbon which this author thought would readily combine with the iron to form carbides.

In the discussion of this paper J. T. Burwell refers to a series of U.S. war-time reports issued between 1944 and 1946 which had been released by the National Advisory Committee for Aeronautics. Their authors, L. O. Brockway, W. A. Vierthaler, T. P. Clark and others, record investigations by electron and visual microscopy, as well as by X-ray and electron diffraction methods, of cast-iron piston rings and nitrided cylinders and rings. The nitrided surfaces became smeared during the operation of the engine and "a metallic layer that consisted of a virtually amorphous crust with an underlayer of finely fragmented crystals was deposited on the ring face." ". . . the vitreous top layer had a high resistance towards oxidation and corrosion." They suggest that the smooth portion of the coating was apparently formed by a melting and flowing of the surface as a result of friction-developed temperatures; whereas the granular portion of the coating was caused by fragmentation and subsequent smearing of the strained surface crystals as a result of elevated temperatures and high surface shear. The smeared surface might flash-melt to a depth of 0·0001 in (as indicated by a diamond furrow mark). The metallic lustre was high and the surface was corrosion resistant and very hard. Proportions of Fe_2O_3, Fe_3O_4 and nitrides were found.

The introduction of nitrogen had greatly interested H. Schottky and H. Hiltenkamp[3] at an earlier date; they showed a significant rise to occur in the nitrogen content of running surfaces. The early work by G. A. Tomlinson[4] in the National Physical Laboratory showed that oxidation could occur in adhesion phenomena with ferrous metals. It is considered, however, that the oxides and nitrides are formed at lower temperatures than those involved in the formation of the white constituent herein referred to.

OTHER EXPERIMENTAL RESULTS

Apart from the metallographic changes noted above, observations were made of scuffing loads and of weight losses in preliminary wear tests. Some of the main results are given below as being of additional interest.

The scuffing load for castor oil for a ball running on three piston ring segments was about 500 kg, compared with 250 kg for plain mineral oil (the corresponding values when four balls were used was 75 and 60 kg). There was no difference when the free fatty acid (1·6%) was carefully neutralized and the soap removed, indicating that the glyceride was the effective lubricant. The addition of 1% ricinoleic acid to plain mineral oil had no effect on its scuffing load. Several additives were tried, including the anti-wear additive tricresyl phosphate, but the only one giving an increase of scuffing load with piston rings was 1% of the thio-ether that was used at one time as a mild extreme-pressure lubricant for back-axles of vehicles; the scuffing load was as high as with castor oil. The wear at loads just below the scuffing range was greater with the thio-ether than with the plain mineral oil. This might provide some explanation of the high scuffing load for the thio-ether solution as high points would be worn away and local welding thus be

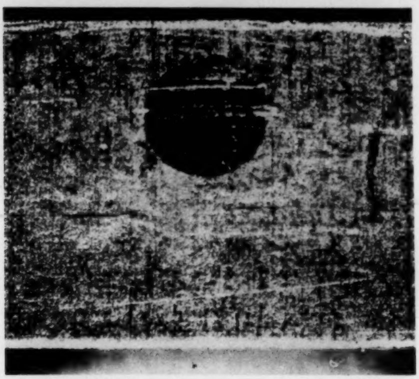

Fig 2. Wear impression (no scuffing) on plain piston ring Load, 190 kg. × 25

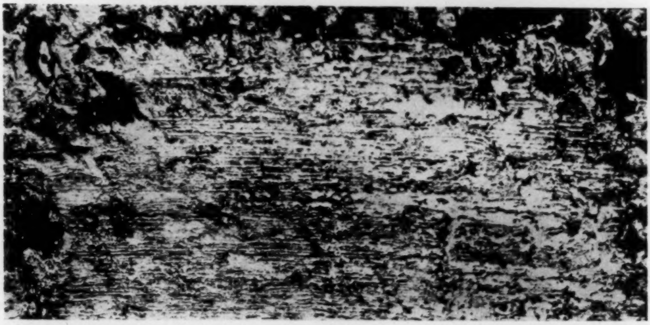

Fig. 3. Wear impression on piston ring segment, 190 kg load, showing some white constituent. × 150

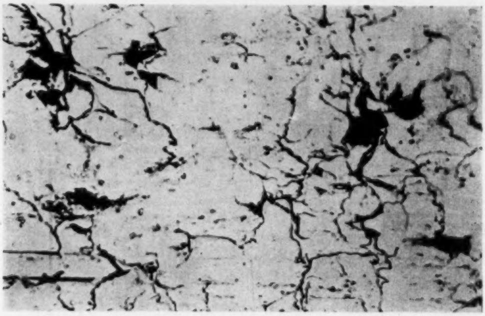

Fig. 4. Typical "seized" piston ring (from engine) showing white constituent and cracking. × 500

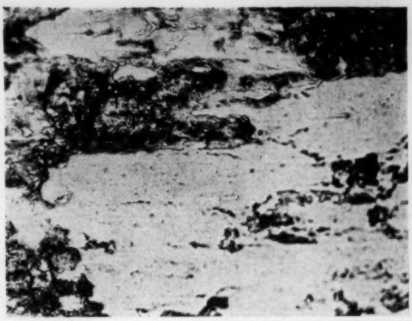

Fig. 5. Typical piston ring which has "feathered" (surface flow) during running-in in engine. White constituent formed. × 500

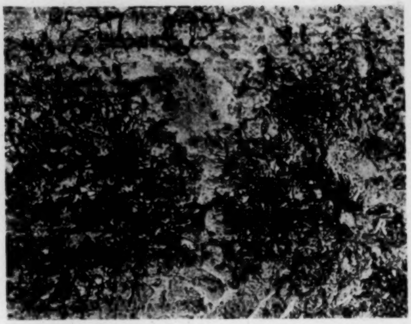

Fig. 6. Typical piston ring after running-in in engine satisfactorily with castor oil. × 500

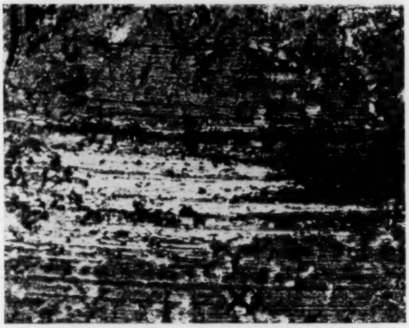

Fig. 7. 60 kg load on ball applied to piston ring segment for 20 min in plain mineral oil. White constituent in moderate quantity. No scuffing. × 150

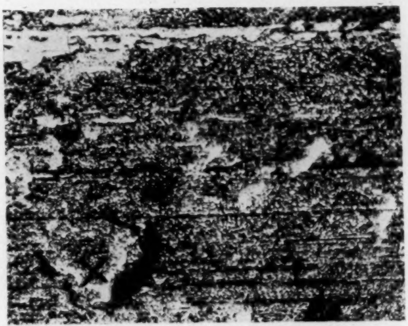

Fig. 8. Enlarged portion of Fig. 7. Corresponding portions marked with a cross. × 500

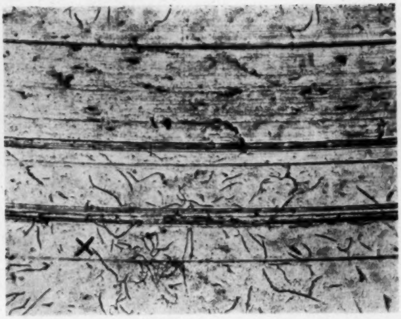

Fig. 9. Similar conditions to Fig. 7 but castor oil used instead of mineral oil. No white constituent formed. × 150

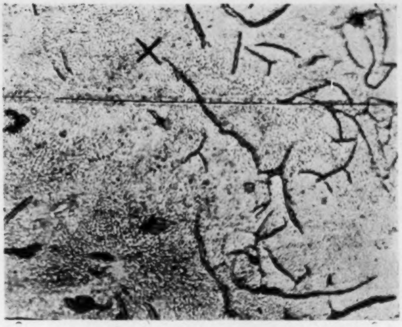

Fig. 10. Enlarged portion of Fig. 9. Corresponding positions marked with a cross. × 500

Fig. 11. Wear track on ball run in castor oil. 60 kg load on ball for 20 min. No white constituent. × 150

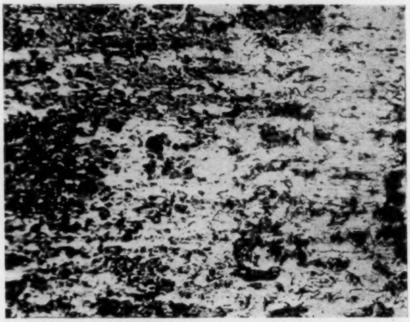

Fig. 12. Surface appearance of wear cavity in piston ring segment. 250 kg on ball for 1 min in mineral oil. Not scuffed. Much white constituent present. × 500

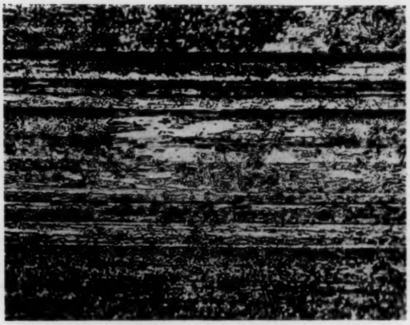

Fig. 13. Wear track on ball run in plain mineral oil. 250 kg for 1 min. Not scuffed. Compare with Fig. 12. Some white constituent present. × 500

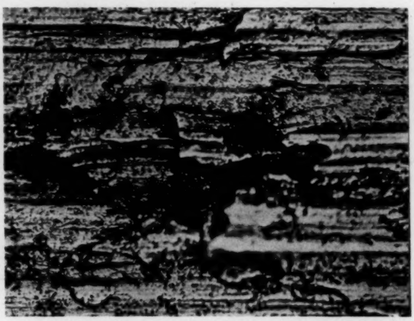

Fig. 14. Piston ring segment in mineral oil. 250 kg on ball for 1 min. Scuffed. Much badly cracked white constituent. × 500

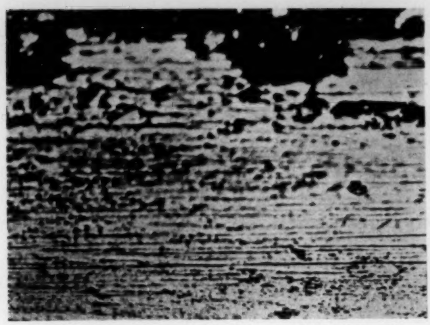

Fig. 15. Piston ring segment with 220 kg load on ball for 1 min in mineral oil. Compare with Figs. 12 and 14. No scuffing. Much white constituent formed. × 500

Fig. 16. Ring segment from same test as Fig. 15 after long polishing with alumina and chromic oxide to remove most of white constituent. × 500

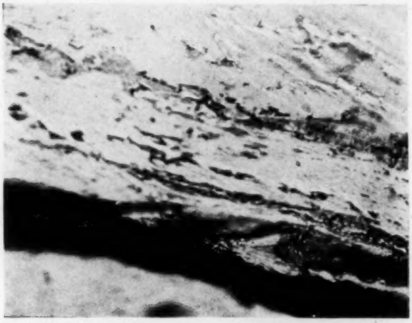

Fig. 17. Four-ball test. Scuffed. 75 kg in mineral oil for 1 min. Much white constituent. × 500

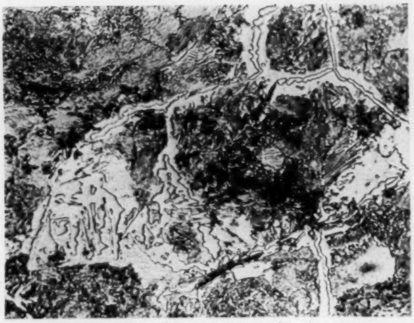

Fig. 18. Microstructure of carburized pure iron. Carbon content over 0·9%. × 500

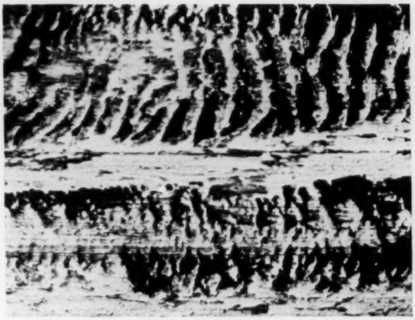

Fig. 19. Chatter marks due to scuffing with ball running on pieces of carburized pure iron with graphite in oil. × 500

deferred; this explanation does not hold for castor oil as the wear was less than with plain mineral oil.

That the anti-wear additives did not show good anti-scuffing (extreme pressure) properties is in agreement with Beeck, Givens and Williams'[(5)] conclusions; moreover, at high loads approaching scuffing, 1½% solutions gave no lower wear than plain mineral oil. Turning now to low load results these authors' conclusions on the benefits in wear reduction by phosphorus and arsenic-containing additives, as typified by tricresyl phosphate and triphenyl arsine, were confirmed. This result was obtained both for hard steel on hard steel (4-ball tests) and for hard steel on piston ring segments (at 20 kg and 60 kg respectively for 20 min). However, in the present work wear reduction (though not to the same extent as with these materials) was also obtained with even the sulphur and chlorine compounds of the extreme-pressure type that Beeck, Givens and Williams said would generally not be able to reduce wear. Amongst further results it was found that 0·2% colloidal graphite was not effective as a wear reducer under these conditions. Castor oil was an effective wear reducer when tested with ball on balls; with a ball on piston ring segments there was the same wear of the ring segments as with the plain mineral oil, but that on the ball was much less. The same result was obtained with castor oil without free fatty acid, and with 1% ricinoleic acid in mineral oil; with 1½% oleic acid in mineral oil the wear on both rings and balls was reduced to a small value.

As already mentioned the results obtained are regarded as no more than pointers to what may happen in running-in piston rings in an engine. In this sense, however, it is thought that the result with castor oil and 1% ricinoleic acid in mineral oil is probably significant and is indicative of what should be sought in running-in: as near perfection as possible in the harder cylinder surface and no alteration whilst running-in (this corresponds with the ball surface), and rapid initial wear of the rings in order that they shall mate as quickly as possible with the cylinder (this corresponds to high initial wear in the ring segments). Beyond such specific indications there is a complex of features in each wear test that would take much experiment to analyse. Mention has already been made of the change of relative wear rates if the load was increased; there was also a change with time of running.

Experiments were made with two chemical surface pre-treatments. One was an etch with nitric acid intended to remove superficial ferrite. There was no improvement in scuffing load, using mineral oil, and the wear of piston ring segments and ball at low loads was only slightly better than with plain rings. The other treatment was phosphating (phosphoric acid and zinc phosphate). There was a striking increase of scuffing load with plain mineral oil, the top load of the apparatus (750 kg) being reached. There was also a decrease of wear at low loads, both of the ball and the rings. (The measured wear in this case is not indicative of the running-in behaviour of phosphated rings, which is quick because of the friable nature of the surface; it is due to the ball quickly getting through the surface layer.) The engine experience showed phosphated rings to be very much superior to those etched with nitric acid.

ACKNOWLEDGMENTS

The work described above has been undertaken as part of the research programme of the National Physical Laboratory and this paper is published by permission of the Director of the Laboratory.

The authors are grateful to Mr. C. Wainwright for his X-ray examination of the specimens referred to and for the interpretation of the structures observed, and desire also to acknowledge the assistance rendered by Mr. P. Tothill and by Mr. G. C. H. Jenkins in connexion with the experimental work.

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(*For Discussion see page* 78)

DISCUSSION

Mr. A. A. Milne: Besides the metallurgical changes that occur on scuffing, described by the authors, there are other physical and geometrical effects of considerable interest. In experiments on the reciprocating machine, described by Dr. Barwell, in which a small area, $\frac{1}{40}$ in^2, is rubbed against a strip reciprocating over a $4\frac{1}{2}$ in stroke, the speed has a marked influence on the load at which scuffing occurs between steel specimens. Thus in one example, whereas this load was above 200 lb at 500 r.p.m., it was only 35 lb at 1 250 r.p.m. On examination of the scuffed surfaces, it was found that metal had been melted or torn from the small area specimen and distributed in discrete blobs on the strip. At the low speeds, associated with high scuffing loads, these blobs were few, but large; at the higher speeds they were small, but many. At still higher speeds scuffing, as defined above, did not occur, but at loads of over 30 lb rapid wear took place, material being removed from both surfaces and distributed as debris in the oil.

The mechanism of this phenomenon seems to be that at some critical load, varying approximately hyperbolically with speed, instability of the lubrication occurs at scattered points. The lubricant film is pierced, metal-to-metal seizure takes place, the surface temperature rises sharply, more quickly on the small area specimen than on the strip, and metal is melted and smeared over the strip. At low speeds a large amount of metal is thus removed; at higher speeds the regions of instability are slid apart more quickly and less metal is melted. At still higher speeds the surfaces are slid apart so rapidly that the melted metal has no time to cool on to the strip, and so is left in the oil as debris.

In this connexion the paper by Mr. Lane suggests that the criterion for the scuffing load may be a critical temperature reached by one or other of the surfaces. The small area, being in contact the whole time, will reach a higher surface temperature than the strip, which is in only intermittent contact. This would also explain the approximately hyperbolic dependence of scuffing load on speed, with slight variation due to a non-uniform coefficient of friction.

Mr. J. E. Stringer: Bearing in mind that certain cast-iron valve plates now used in hydraulic machinery are inclined to exhibit scuffing troubles not reported to have been encountered in earlier days, have the authors considered that some factor in the manufacturing of cast iron might have changed, comparing present-day production with conditions say twenty or thirty years ago? Or should such changes in performance be attributed to changes in the oils, such as might occur through improved refining technique removing traces of impurities that assisted lubrication?

Authors' reply: We thank Mr. Milne for his contribution, and in reply to Mr. Stringer we think that improvements in the quality of cast irons are much more likely to explain the different rubbing behaviours of the old and new irons than changes in the oils, though there have been developments in refining techniques which tend to reduce somewhat the quality for rubbing contacts.

Surface welding and the extreme pressure lubricant

By Prof. G. I. Finch, M.B.E., D.Sc., F.Inst.P., F.R.S., and R. T. Spurr, B.Sc., Imperial College of Science and Technology, London

When two surfaces are brought into contact the surface oxide films prevent intermetallic welding. The films may be ruptured by sliding the surfaces over each other, or by applying sufficient pressure to cause plastic flow at the interface. The ease with which surfaces weld on sliding depends upon their rigidity and the nature and thickness of the surface films.

Extreme pressure additives react with the surface oxide to form a compound which is more fusible than the metal. If the local temperature should rise sufficiently during sliding, this compound will melt and smear over the surface, and act as a temporary lubricant.

The surface of a metallic single crystal can be rendered atomically smooth by appropriate anodic polishing. Such a surface has, in general, a waviness of small amplitude and long wavelength. If suitable precautions are taken the surface oxide film can be restricted to a few molecules in thickness. Two such single-crystal surfaces do not adhere if pressed together at room temperature, provided the pressure is not sufficient to produce extensive plastic flow; for the surface film, thin though it may be, prevents metal-to-metal contact and the consequent welding together of the two surfaces. If general flow takes place the increase in surface at the interface ruptures the oxide films, and cold welding occurs. Consequently, in this case the protection afforded by the oxide layer is determined by the rigidity of the underlying metal rather than by the nature of the oxide.

If, however, a copper single-crystal surface is slid over a similar surface the oxide layer is penetrated and a cold weld formed. The oxide may be rubbed away from a high spot; or metal may be displaced by a scratching fragment or other debris and pile up at the head of a scratch, and so displace the film on the opposing surface. Each weld grows rapidly; the first small welds are broken by the shearing force, and they in turn disturb a larger amount of surface and so form increasingly larger welds, until these can no longer be sheared by the tangential force and total seizure occurs. Copper single crystals pressed together gently with the fingers weld so strongly after sliding only a fraction of a millimeter that they are difficult to pull apart. In this case the ease with which the surfaces weld together depends not only on their rigidity but also on the nature and thickness of the surface film. During sliding the area of contact increases rapidly for soft ductile metals so that these tend to weld more easily than harder, more elastic metals. Thus copper single crystals weld more readily than similar crystals which have been mechanically polished to form a work-hardened surface layer, or than electropolished polycrystalline specimens where deformation in each crystal grain is to a greater or lesser extent restricted at its boundary. Again aluminium, which is harder than tin, welds much more easily than the latter to copper, for the cuprous oxide is worn away more quickly by the very hard alumina than by the tin oxide. Similarly,

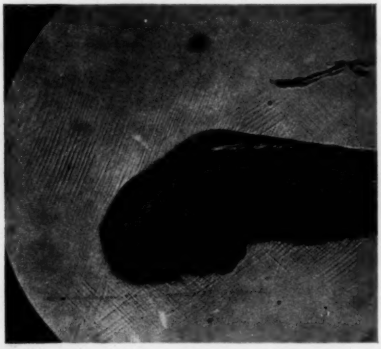

Fig. 1. Surface damage resulting from weld formation between a pair of copper single crystals. Note slip lines formed ahead of and at the sides of the main damage area. × 450.

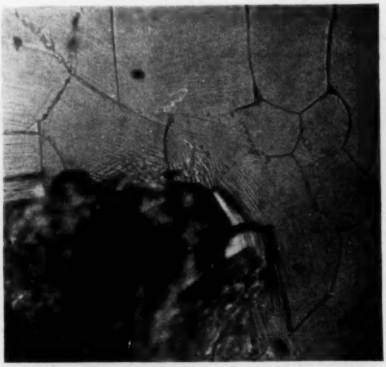

Fig. 2. Damage and slip lines at the head of a weld formed by sliding polycrystalline copper surfaces together. × 450.

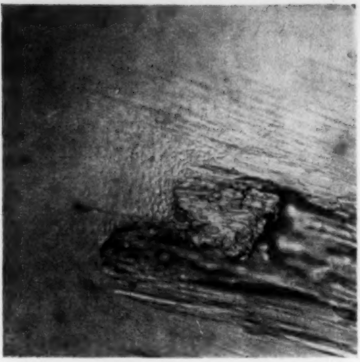

Fig. 3. Scoring damage due to welding between a pair of copper single-crystal sliding surfaces. × 450.

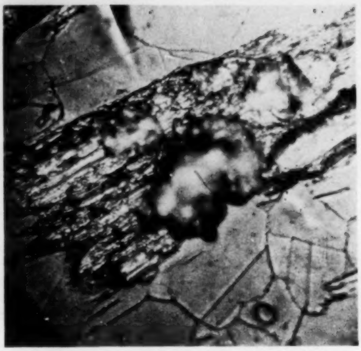

Fig. 4. Fragment of aluminium left adhering to a copper surface after sliding on copper. × 450.

there is considerably more welding when aluminium instead of copper is slid over an iron single crystal. With pairs of hard surfaces, or surface pairs of widely differing rigidities, full seizure does not take place with moderate loads and low rates of sliding because of the difficulty of penetrating both the oxide layers; nevertheless, metallic welds of small extent are formed and broken, as is easily seen under the microscope.

In sliding, considerable damage is done to the surfaces. Slip lines surround the welds, changing direction at the crystal boundaries to follow the appropriate glide planes and, particularly with single crystals, extend far across the surface and into the body of the crystal (Figs. 1 and 2). At the weld itself the crystal structure is broken down and the metal becomes work-hardened. Because of this work-hardening the weld generally breaks within the bulk of the metal and does not shear at the interface, and in the case of dissimilar metals a fragment of the weaker metal is dragged out and left adhering to the opposing surface (Figs. 3 and 4).

In metal pairs capable of forming a more fusible eutectic, it appears that the actual interface of the weld has the eutectic composition. Thus, if tin and lead surfaces which have been slid together and so caused to cold weld, are heated in a vacuum, the surfaces part at the melting point of the eutectic. Similarly, lead and bismuth separate easily at the melting point of the lead-bismuth eutectic.

The oxide film which forms naturally on a metal surface gives very effective protection provided the metal affords it adequate support. If electropolished copper specimens are exposed for some time to the air they become increasingly difficult to weld, but if treated with potassium cyanide to remove the oxide they once again weld easily. The oxide film may be very thin but, being formed at room temperature, is amorphous and, therefore, isotropic and tough. The coefficient of static friction for light loads is low, and much of the work of friction is done in scratching. When intermetallic welding does happen it occurs mostly at high-spots which have been previously wiped clean of oxide. If, however, the copper surface is so oxidized as to form a crystalline layer of cuprous oxide sufficiently thick to give interference colours, the oxide surfaces weld together very easily and the coefficient of friction is correspondingly increased. The amorphous film formed at the surface of the crystalline oxide on cooling and exposure to air again gives considerable protection and reduces the friction by inhibiting welding of the crystalline oxide films. Though some intermetallic welding may occur, it is the adhesion of the oxide film which now becomes important. Scratching, welding together of the oxide films, shearing, and pulling out can be seen to take place within the oxide films.

When films other than oxides are formed, it is found that an amorphous film is usually more effective in reducing intermetallic welding than the corresponding crystalline film. The properties of the sulphide film on copper, however, are of particular interest, for in this case crystalline films of about 1 000 A in thickness strongly resist intermetallic welding and give a low coefficient of friction under moderate pressures and low rates of sliding. There is no intermetallic contact, welding and its consequences being confined to the sulphide films.

The nature of the protection afforded by the extreme-pressure additives is, however, quite different. Here the sliding surfaces are of hard ferrous material and the chemical films may be only 100 A or even less in thickness. Under very severe conditions of sliding, high temperatures will be developed at the surfaces. But before the frictional temperature at areas of rubbing contact becomes high enough to soften the underlying metal and thus rob the oxide layer of its support, the additive reacts with the oxide to form a layer of a compound such as a chloride, oxychloride, or sulphide which, unlike the oxide, is more fusible than the metal. If the local temperature should rise sufficiently to melt this compound, some of this molten layer will smear over the surface and act as a temporary lubricant.

DISCUSSION

Dr. A. W. Crook: I would like to mention an experiment which we have carried out and which gives direct evidence in support of a suggestion due to Sampson, Morgan, Reed and Muskat(1) that the strength of the metallic junctions which may be formed when two metal surfaces are brought together depends upon the time available for their formation. We have an apparatus in which force as a function of time is measured piezoelectrically throughout the impact of two metal bodies. If a force of adhesion develops between the bodies during impact, this is shown up by the force becoming negative before the bodies separate.

Bowden and Tabor(2) have shown that a steel ball adheres strongly to a clean indium surface into which it has been pressed. Similarly, two freshly cut surfaces of indium if pressed together adhere with a force comparable with that with which they were loaded. We have used cylinders of indium in our impact apparatus; clean surfaces were cut on these cylinders within the two minutes previous to their collision. A typical result is that in an impact in which a maximum force of 11×10^6 dynes was reached, an adhesive force of $1{\cdot}3 \times 10^6$ dynes developed and the area of the dent formed was $8{\cdot}2 \times 10^{-2}$ cm^2. Similar cylinders of indium have been pressed together statically. In a static test in which the load was $3{\cdot}3 \times 10^6$ dynes the contact formed between the cylinders withstood a pull of $3{\cdot}6 \times 10^6$ dynes and the area of contact was $7{\cdot}0 \times 10^{-2}$ cm^2. In spite of the area of contact being less in the static experiment the adhesion is nearly three times greater than in impact.

The separated surfaces have been examined: those of the cylinders used in static experiments are rough, suggesting the tearing of metallic junctions; those of the cylinders used in impact are smooth. These experiments show that in the period of impact (2 msec) there is not time for adhesion between the two surfaces to be fully developed.

Dr. D. Clayton: The result found by Dr. Crook might be due to air trapped between the colliding surfaces.

Dr. A. W. Crook: In reply to Dr. Clayton I would like to say that it seems probable that the cause of the time effect in the development of adhesion is that metal has to penetrate protective layers which may exist at the interface and that under some dynamic conditions there is not time for this penetration to reach completion. We have as yet insufficient evidence to allow us to suggest whether the effective intervening film is trapped air or the oxide which would be present even on a freshly cut indium surface.

Dr. J. S. McFarlane: I was very interested in this paper as the results described are closely related to some results obtained by Dr. D. Tabor and myself, working in Dr. F. P. Bowden's laboratory at Cambridge.(2,3)

We measured the adhesion of a hard steel ball to blocks of indium, lead, tin and other soft metals, and found that this adhesion could be very powerful. For instance, if the steel was pressed on to an indium surface by a load of 1 kg-wt, roughly 1 kg-wt was required to pull the metals apart again.

In discussing the phenomenon of adhesion or surface welding, Mr. Spurr has placed much emphasis on the important effect of surface films of oxides and other compounds, but he has not mentioned another factor which I believe to be of at least equal importance: namely, the mechanical properties of the metals themselves. It is well known that if an indentation is produced in a metal surface by pressing a hard steel ball on to it under load (as in a Brinell test) the radius of curvature of the surface of the indentation, measured after load and ball have been removed, is greater than the radius of curvature of the ball which produced it. This effect is often called "shallowing" and it is due to the elastic recovery which takes place in the metal when the applied load is removed.(4) It is clear that such elastic recovery, by destroying the "fit" between the surfaces, will also tend to destroy any intermetallic junction which may have been formed between them when in contact under load. In fact, the surfaces will pull apart as the load is removed, and no measurable adhesion will remain. This effect will be very much more marked for hard metals than for soft and ductile ones where the elastic recovery is very small and weak. This, I believe, is the explanation of the fact that it is very much easier to obtain adhesion (or "cold-welding") between soft metals than between hard ones.

It is certain that oxide and other films on metals greatly modify their surface properties, but it is interesting to note that our results indicated that films of greasy matter exerted a much more profound influence on adhesion than did oxide films, unless these were very thick. Indeed it appeared likely that a considerable part of the total adhesion between the steel ball and the indium block derived from the interface between the thin oxide films present on both metals. Without assuming that the oxide films underwent some sort of catastrophic breakdown on being stretched by a few percent, it seemed impossible to account for all the adhesion from the small area of metal/metal contact.

Thus in seeking a full explanation of adhesion and surface welding, consideration must be given not only to their surface properties but also to their bulk properties.

Dr. F. T. Barwell: The simplified theory whereby the force of friction is equated to that required to shear junctions tangentially is unconvincing to the engineer because the normally accepted criteria of failure indicate that rupture would occur on planes inclined to the tangential interface. It would therefore be of interest if the authors could indicate whether the damage they ascribe to the shearing of junctions was consistent with shearing occurring in the interfacial plane or on planes inclined thereto.

Authors' reply: In reply to Dr. McFarlane, our experiments were carried out with surfaces which had been abraded flat and electropolished to give an atomically smooth finish. With light loads there should have been little tendency for the surfaces to be forced apart by elastic recovery or removal of the load. Thus the nature and thickness of the surface film and the support afforded to it by the underlying metal determine the behaviour on sliding.

When the steel ball is pressed into indium relative motion occurs between the two surfaces. In a somewhat similar experiment we have found that sliding, as shown by microscopic radial scratches, with consequent severe rupturing of the surface film, occurs before a lead disk adheres to two flat parallel copper disks between which it is compressed.

In reply to Dr. Barwell, we wish to say that in the experiments described the welds did not shear in the plane of the interface, but ruptured in the body of the specimen, leaving small fragments adhering to the surfaces.

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An investigation of surface damage using radioactive metals

By E. RABINOWICZ, B.A., Research Laboratory on the Physics and Chemistry of Rubbing Solids,
Department of Physical Chemistry, University of Cambridge

Experiments have been carried out in which a radioactive metal hemisphere slides over a non-radioactive metal surface, and the amount and nature of the transferred material are examined autoradiographically. It is found that metal transfer takes place in the form of discrete fragments, and that well-lubricated surfaces give less transfer than clean surfaces by factors of 400 or more. On heating well-lubricated surfaces, both the coefficient of friction and the amount of metal transfer increase markedly at the melting point of the surface film. The metal transfer, however, in contrast to the friction, is sensitive also to temperature change below the surface film's melting point, and this is explained as due to the softening of the surface film near its melting point. In some cases, large non-radioactive fragments picked up on the radioactive slider prevent the transfer of radioactive fragments, and examples of this effect are shown.

Experiments on surface damage have a dual importance as part of a study of lubrication. The first is economic—it is more important in most cases in industrial practice to reduce the wear than to reduce the friction—and the second is bound up with the fact that we can derive useful information on the mechanism of friction by studying the related quantity, surface damage. Bowden, Moore and Tabor(1) showed that the friction of metals is due largely to localized adhesion at the points of contact. During sliding, the high projections of both surfaces come into contact, weld together, and are torn apart. Sometimes the welded junction is stronger than the metal on either side, and in this case a fragment of one metal is torn off on to the other. Owing to the extremely small size of some of these fragments, a sensitive method of detection must be used, and a satisfactory one is the radioactive tracer method, detection of the radioactivity being either by Geiger counter, after Sakmann, Burwell and Irvine,(2) or photographic plate, after Gregory.(3)

The method used in the experiments to be described involved the carrying out of friction runs on the Bowden–Leben(4) friction apparatus, which allows the simultaneous measurement of the friction, temperature and velocity of sliding. A radioactive hemispherical slider was used, and the transfer of activity to the bottom flat

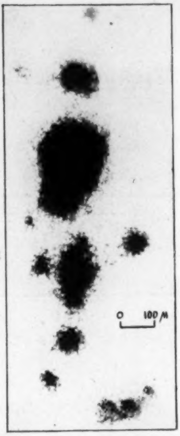

Fig. 1. Autoradiograph of same surface as Fig. 2. The radioactive copper fragments have produced circular blackened regions surrounding them

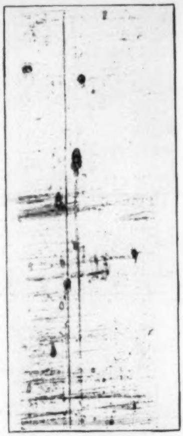

Fig. 2. Micrograph of steel surface after passage of radioactive copper slider. Some transferred copper fragments may be seen

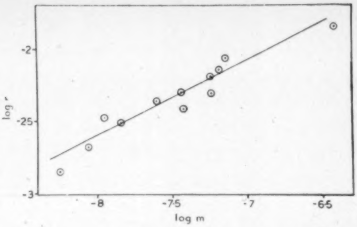

Fig. 3. The logarithm of the radius (in cm) of the blackened regions in Fig. 1 plotted against the logarithm of the mass (in g) of the corresponding fragment in Fig. 2. A line of slope ½ fits the points

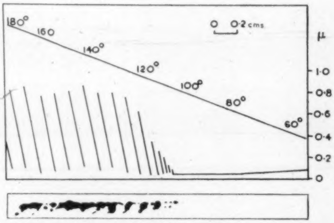

Fig. 5. Friction trace and corresponding autoradiograph for copper sliding on copper lubricated by palmitic acid, showing breakdown of lubrication at 105° C

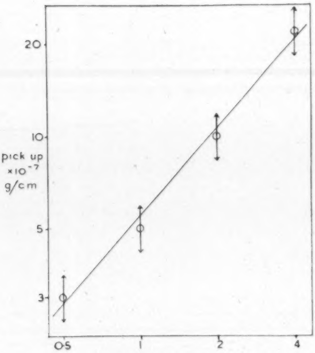

Fig. 4. Mass of pick-up plotted against load for platinum lubricated by paraffin oil showing that the pick-up is proportional to the load

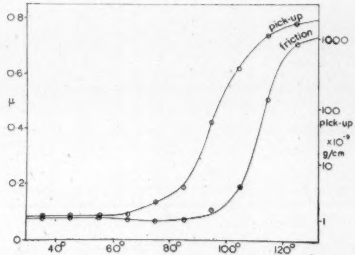

Fig. 6. Friction and pick-up values plotted against temperature for copper sliding on copper lubricated by palmitic acid. Load, 2 kg; speed of sliding, 0·01 cm/sec

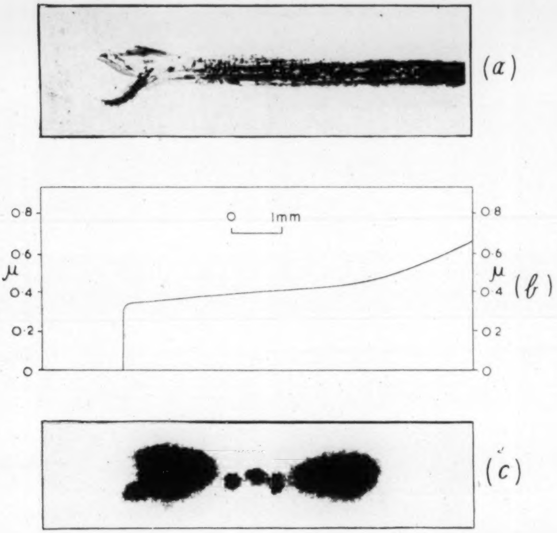

Fig. 7. Radioactive platinum hemisphere sliding on silver (1 kg load). (*a*) Micrograph showing changed appearance of track as sliding continues; (*b*) corresponding friction trace showing increase of friction during sliding; (*c*) autoradiograph showing that pick-up ceases once all the surface of the platinum slider has been covered by silver

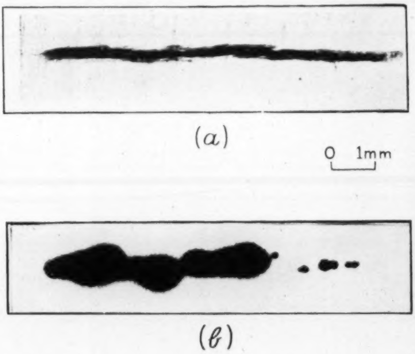

Fig. 8. Radioactive copper hemisphere sliding on copper (2 kg load). Pick-up suddenly reduced by a fragment of inactive copper adhering to the slider. (*a*) Micrograph; (*b*) autoradiograph

strip was studied. The sliders were activated in the B.E.P.O. at the Atomic Energy Research Establishment, Harwell; they were made of copper, cadmium, zinc, platinum, silver and stainless steel. To detect the activity after a sliding experiment, the bottom specimen was put on a photographic plate, which blackened locally. Except where high quantitative accuracy is required, the photographic method has advantages over the Geiger counter in sensitivity and in the range and variety of information obtained.

Normally, the photographic method will detect down to 10^{-12} g in favourable cases, and visual comparisons of the density of blackening with that produced on step-wedges enable estimates of the mass of pick-up to be made with a probable error of about 30%. This accuracy is usually adequate, as the reproducibility of wear experiments is almost always worse.

Fig. 1 shows a typical autoradiograph of a friction track. The pick-up has not been uniform, but a number of discrete fragments have been transferred. The blackened circle surrounding each fragment depends on the size of the latter, as may be seen by comparison with Fig. 2, which shows a photomicrograph of the same track. In fact, the square of the radius of each blackened circle is proportional to the mass of the corresponding fragment, and Fig. 3 confirms this for the fragments of Figs. 1 and 2.

It is found that the amount of material transferred during sliding depends very markedly on the lubricant. The table shows some results for platinum.

Transfer of material on sliding platinum over platinum

Load = 2 kg. Speed = 0·01 cm/sec

Lubricant	*Coefficient of friction*	*Pick-up*
None	0·65	4 × 10^{-5} g/cm of track
Cetane $C_{15}H_{31} . CH_3$	0·52	10^{-6}
Cetyl alcohol $C_{15}H_{31} . CH_2OH$	0·38	2 × 10^{-7}
Palmitic acid $C_{15}H_{31} . COOH$	0·14	10^{-7}

It will be seen that, while the friction changes by a factor of 5, the pick-up changes by a factor of 400. Chemically reactive metals give even less pick-up with palmitic acid because they react to form the soap (Bowden, Gregory and Tabor,⁽⁵⁾ and Shooter⁽⁶⁾).

The pick-up does not always vary in a simple way when the load is changed, but Fig. 4 shows a case where the pick-up is directly proportional to the load, and the line of slope unity fits the points well.

Of great interest is the variation of metal transfer with temperature. Fig. 5 shows a friction trace and the corresponding autoradiograph for copper on copper with palmitic acid. In this case the lubricant breaks down at about 105°, both the friction and pick-up increasing markedly at this temperature, which is close to the softening point of copper palmitate, showing that the acid has reacted with the surface. (The melting point of palmitic acid is 64° C.)

Fig. 6 shows average friction and pick-up values for a number of runs. The pick-up and friction vary together, but the pick-up begins to increase at a lower temperature than does the friction. This is of some importance, for in the region 60–90° C there is a decrease of friction accompanied by an increase of pick-up. The reason is that for well-lubricated surfaces the friction is determined almost exclusively by the shear strength of the lubricant. When we raise the temperature, the copper palmitate becomes softer, and at first the friction will decrease. However, this softer lubricant layer provides poorer protection to the surface, and hence surface damage and pick-up will increase.

Lastly, a case will be described in which the radioactive method failed. Bowden, Leben and Tabor⁽⁷⁾ found that platinum sliding on clean silver picked up so much silver as to cover its surface completely, and the sliding became that of silver on silver. Fig. 7 shows a similar run using radioactive platinum. Fig. 7(*a*) shows a photomicrograph of the surface, and it will be seen that the smooth track characteristic of the sliding of unlike metals soon changes to the torn track of like-metal combinations. The friction increases, but the pick-up, as shown in Fig. 7(*c*), suddenly ceases when all the platinum surface of the slider becomes "shielded" by adhering silver. Fig. 8 shows a similar occurrence for copper on copper; again beyond a certain point there is no pick-up except at the edges of the track, and on the corresponding micrograph there is some indication of a large fragment torn from the track at that point.

But it must be pointed out that this "shielding" does not occur often, and can usually be recognized whenever it occurs. In practice the radioactive method works perfectly satisfactorily.

ACKNOWLEDGMENTS

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The effect of lubrication on friction, wear and abrasion

By P. GRODZINSKI, A.M.I.Mech.E., Diamond Research Department, Industrial Distributors (Sales) Ltd.

The lubrication of a grinding surface is one of the most important items in abrasive processes, and experimental work on it is reported. Recent tests, in which the coefficient of friction was measured by an electronic dynamometer, employed a cast-iron disk in contact with a lubricated diamond surface. Using various oils, the coefficient of friction was generally below 0·08 without diamond powder and about 0·11 with the powder.

The considerable effect of lubrication on abrasion is well known. As lubricants are used in bearings to reduce wear and friction, it may appear somewhat contradictory that similar fluids should also be used to increase wear. In considering the performance of well-lubricated engine bearings the presence of fine hard particles cannot be excluded,(1) whilst in the abrasive process a definite concentration of such abrasives is intentionally added.

The two phenomena of interest are friction and wear, and by the latter is meant the amount of material removed by abrasion. The assumption that a high rate of abrasion is accompanied by high friction(2) and conversely that low friction is indicative of low wear, has already been disproved experimentally.(3)

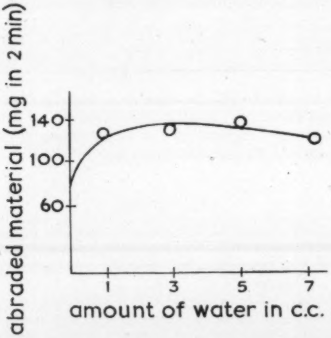

Fig. 1. Influence of amount of water on abrasive action after Kruel.(5)

In abrasive processes, the following factors must be considered:(4) (1) grinding speed (very high, polishing speeds perhaps somewhat lower); (2) auxiliary (lapping) movement (relatively slow with changing direction of attack); (3) pressure (definite, constant, but preferably flexible); (4) grinding and polishing grain (of suitable and uniform size); (5) lubrication of grinding surface (by water, oil, or other fluid); (6) type of "bearer" or "carrier" medium for "loose" or "bonded" grain.

Each of these factors has a large effect on the result, and whilst the first three factors are determined by the particular set-up, the other three will be vital in obtaining the optimum result. It is therefore generally difficult to isolate the effect of lubrication. The effects of the quantity and nature of the lubricant must be considered.

QUANTITY OF LUBRICANT

Present practice regarding the quantity of lubricant is very varied. In diamond grinding there is a distinction between wet and dry preparation of the cast-iron disk: in the former the diamond dust is mixed with oil before application and is applied as paste; in the latter, dry powder is applied to a slightly moistened disk. Bonded diamond grinding wheels are used, either dry, damp, or in a wet state, i.e. flooded with lubricant. At present it is not clear which is the better. Kruel(5) observed (Fig. 1) that the rate of abrasion first increased from the dry state and only slowly decreased with a larger supply of lubricant (water). He observed that the speed of the lap had a great effect on the abrasion. The abrading capacity, which for the optimum amount of lubricant (water) is assumed to be proportional to the peripheral speed, can be substantially changed.

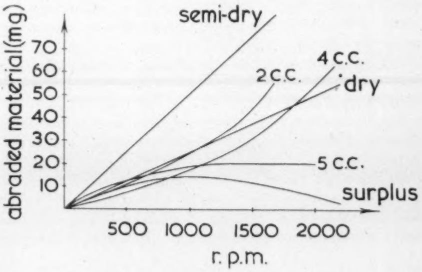

Fig. 2. Abrasive action influenced by grinding speed and water supply after Kruel.(5)

Generally, the less water supplied (Fig. 2) the greater the abrasion at any particular speed. The optimum, however, is not dry grinding, but semi-dry. For these conditions a linear relationship between speed and abrasion capacity is established. However, with larger amounts of lubricant the formation of a film between lap and work occurs, particularly at higher speeds, thus reducing the abrading capacity. A smaller amount of lubricant (water) produces the opposite effect as the centrifugal force further reduces the water film. Effective grinding does not always result from high speeds but from the best grinding conditions. For instance, the vibration of a lap changes with the speed, so that tests must be critically assessed with this in mind.

Kruel observed that on changing the grinding pressure (Fig. 3) a linear relationship between pressure and abrasion effect can only be maintained under certain conditions. With large quantities of lubricant a deviation from the straight line occurs, as with speed. When plotted on a log. log. scale the curves become straight lines.

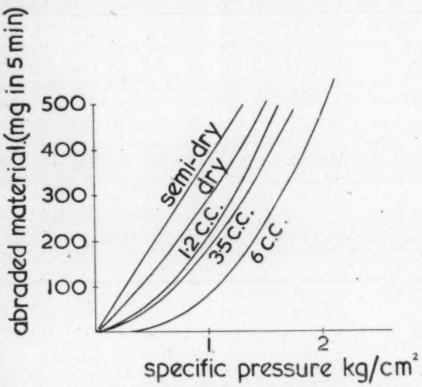

Fig. 3. Abrasive action influenced by pressure and water supply after Kruel.(5)

Similar tests on the abrading of synthetic sapphire with diamond-prepared copper wheels reported by G. Pahlitzsch(6) showed that a surplus of fluid did not materially change the abrasion rate. In using a diamond-dust/oil paste (Fig. 4) for drilling holes in synthetic sapphire no improvement was found above a concentration of 1 : 8, whereas below this concentration there is a considerable increase in drilling time. Hence for economic reasons it is not advisable to use a concentration higher than 1 : 8. Weaker concentrations are said to have the same effect as larger grain sizes.

NATURE OF LUBRICANT

Extensive tests on the influence of lubricant and bearer material on abrasion have been carried out by Knight and Case,(7) using three types of abrasive (emery, alumina, and silicon carbide), three types of lap (steel, cast-iron, and copper) and seven different lubricants from soda-water to lard oil. The same fluid acts differently with different abrasives and with different laps. Changes in viscosity and lubricating properties are suspected but may not be the only factors. Of the 63 combinations tested, 15 were found to give optimum abrasion rates (Table 1). The absence of emery from these is noteworthy, but practically all lubricants tested are included.

Table 1. *Best combination of abrasive, lap material and lubricant* (*Knight and Case*, 1915)

Abrasive	*Lap*	*Lubricant*	*Value (arbitrary units)*
SiC	Steel	Lard oil	3·5
SiC	Copper	Lard oil	3·44
SiC	Cast-iron	Gasoline	3·42
Al_2O_3	Copper	Soda-water	3·39
SiC	Cast-iron	Turpentine	3·37
SiC	Cast-iron	Alcohol	3·35
Al_2O_3	Cast-iron	Gasoline	3·25
SiC	Copper	Turpentine	3·22
SiC	Cast-iron	Kerosene	3·20
SiC	Copper	Soda-water	3·19
SiC	Steel	Machine oil	3·17
Al_2O_3	Copper	Turpentine	3·15
SiC	Copper	Machine oil	3·14
Al_2O_3	Copper	Alcohol	3·10
SiC	Copper	Alcohol	3·09

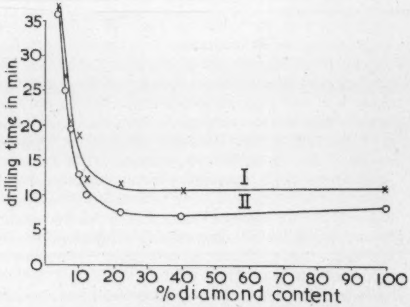

Fig. 4. Grinding with diamond powder made up in paste after G. Pahlitzsch.(6)

Curve I, drill needle diameter, 0·4 mm
Curve II, drill needle diameter, 0·2 mm

Some years ago, cyclohexanol(8) was suggested as a medium for diamond powder in drilling diamond drawing dies, bringing an improvement of 12 : 1, compared with olive oil or lanoline. No attempt has been made to explain this action, but similar improvements were found with a mixture of about 5 parts of carbon tetrachloride with one part of diamond powder. As cyclohexanol is solid below 30° C it can be assumed that its advantage

Table 2. *Friction tests (short time)*

Smoothly turned cast-iron disk, striped (scratched) after turning; plane ground diamond face (area 4·30–4·65 mm²); peripheral speed 5 850 ft/min, ambient temperature 21 to 23° C

Lubricant	*Without diamond powder, load (kg)*						*With diamond powder, 0–2 μ, load (kg)*					
	1·01		1·24		1·46		1·01		1·24		1·46	
	μ_k	°C	μ_k	°C	μ_k	°C	μ_k	°C	μ_k	°C	μ_k	°C
Castor oil	0·084	60	0·076	65	0·072	70	0·138	55	0·125	68	0·123	75
Cyclohexanol	0·079	60	0·084	65	0·075	70	0·114	60	0·117	70	0·123	80
Machine oil	0·074	60	0·068	65	0·068	70	0·109	60	0·097	67	0·092	75
Olive oil	0·069	50	0·068	60	0·071	70	0·099	50	0·097	55	0·096	60
Specific pressure (kg/mm²)	23·4		28·7		33·8		22·7		27·7		32·5	

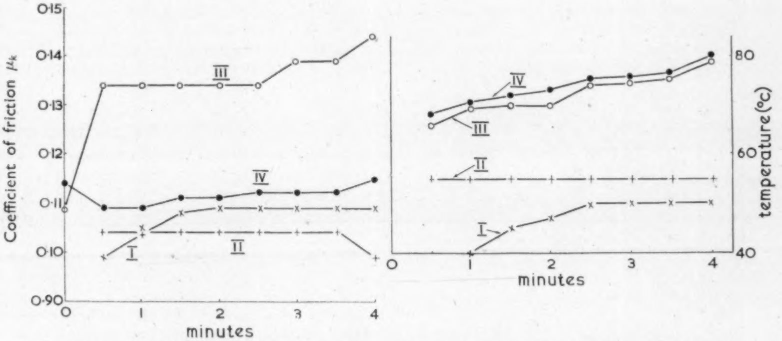

Fig. 5. Variation of friction and temperature with different lubricants and diamond powders.

Curve I, olive oil, 0–2 μ diamond powder; Curve II, olive oil, 4–8 μ diamond powder; Curve III, cyclohexanol, 0–2 μ diamond powder; Curve IV, cyclohexanol, 4–8 μ diamond powder.

in grinding is partly due to the fact that only that part of the paste which performs the grinding operation becomes fluid, whereas the rest remains solid. If, for instance, part of the fluid is thrown off by centrifugal action, it immediately solidifies and therefore is not lost. Similar observations were made with cocoa-butter, a white fat, which was used for suspending diamond powder in drilling sapphire, and proved to be excellent.

Zakoshchikova(9) measured wear and friction on an apparatus consisting of a groove in a ring (to keep the fluid mixed with abrasive), and blocks of the sample pressed against it. He determined the abrasion rate on aluminium, using silicon carbide in a water-alcohol mixture and in 0 to 0·5% solutions of stearic acid in absolute ethyl alcohol. The optimum effect was obtained with 0·1% stearic acid.

W. von Engelhardt(10) found that the differences in the behaviour of various fluids can be explained by the surface energy or, more specifically, by the relative surface boundary limit energy between the solid and fluid state. Unfortunately, in spite of its physical significance the surface boundary limit energy is difficult to determine and he suggests the use of the grinding process itself for this purpose. This, however, presents great difficulties in accurate control: of course, simple laboratory test procedures could be devised but these would have to be correlated with conditions in practice.

In polishing gemstones the acidity of the lubricant seems to have some effect, general practice being to employ water mixed with vinegar or even sulphuric acid. Systematic tests by the Czech Gemmological Institute(11) showed that in polishing synthetic spinel with neutral water (pH 7) and with water to which hydrochloric acid was added (pH 1·2) the following reductions in polishing time on tin/lead laps of different compositions resulted:—

Tin, %	100	80	61·9	40	20	0
Saving in time, %	38	35	34	24·5	12·5	2·2

TESTS

This section has been modified to include the results of more reliable tests made in this Department since the conference.

Friction tests on a plane cast-iron surface were carried out with a diamond having a flat surface of about $4 \cdot 3$ mm^2. The usual fixed pins for holding the "tang" were replaced by a swinging arm, the drag being measured electronically. A newly prepared surface on the scaife was selected for each test and the different oils applied; first without any abrasive and subsequently with it. After each test the ring was cleaned with carbon tetrachloride. Diamond dust of 0 to 2 and 4 to 8 μ size was used as abrasive and, in addition to the drag, the approximate temperature between the diamond and the lap surface was measured by a thermocouple. Initial tests were carried out for 1 to $1\frac{1}{2}$ min, but later on the runs were extended to 4 min. The results are shown in Table 2 and Fig 5.

As the condition of the grinding surfaces changes relatively quickly, there is an appreciable variation of the coefficient of friction and temperature. In the series without diamond dust the coefficient of kinetic friction (μ_k) remained well below $0 \cdot 1$, whereas in practically all tests with diamond powder of 0 to 2 μ it rose well above $0 \cdot 1$. The coefficient of friction with olive oil, the lubricant generally used for these processes, is surprisingly low. Increasing load and increasing specific pressure seem to maintain or even reduce the coefficient of friction.

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DISCUSSION

Mr. A. J. Chisholm: The role of a fluid in an abrasive grinding process can be considered from a somewhat different standpoint to that of Mr. Grodzinski, who has spoken of a gradual transition in the nature of the friction from that occurring in journal bearings to that observed in abrasive grinding processes.

There is some evidence to suggest that grinding is in fact a cutting process in which the abrasive particles act as cutting tools, and the "chips" of material removed are microscopic in size. This appears to be true even when grinding, for example, hardened tool steel. It is suggested, therefore, that grinding is essentially a cutting process, and not a wear process, such as occurs at two sliding surfaces where junctions are formed and material transfer takes place.

In a cutting process, when the cutting speeds are low or when the surfaces of the cutting tool are frequently replenished with lubricant (as occurs when grinding with loose abrasive), the most significant function of the lubricant is to lubricate the "chip" as it slides over the surface of the cutting tool away from the cutting edge. This lubrication assists the formation of a more continuous type of chip and also reduces the energy required to remove a given weight of material.

In the experiments on grinding with loose abrasive described by Mr. Grodzinski, it is possible that the fluids cause an increase in grinding rate, not allowing the abrasive particles to slide more easily over the lap surface, but rather by lubricating the "chips" as they slide over the surface of the abrasive particle. This would allow a given chip weight to be cut more easily, and tend to produce the chips in a more continuous form. It is perhaps not too big a step from these conclusions to imagine that a lubricant would also assist the abrasive particles to start the formation of a chip more easily, and to cut longer chips; this would cause the rate of material removal to be increased. Perhaps the answer to the question "What type of fluid appreciably increases the rate of material removal?" is to look amongst the metal cutting fluids which have been developed for such operations as threading and broaching, where the lubricating effect of the fluid is of primary importance.

If this view of the grinding process is correct, the "friction" force measured by Mr. Grodzinski in his grinding experiments has a component due to the cutting force exerted by the abrasive cutting edges; a reduction in this "friction" force due to the application of a fluid would be caused partly by a reduction in the cutting force. His values of coefficient of friction do not seem strictly comparable with those observed in pure sliding, and the experiments which he has described—though of considerable interest in themselves—are perhaps too complicated by the addition of the cutting component to give any fundamental information on the mechanism of friction and wear as normally understood.

Author's reply: My paper not only dealt with grinding processes, but also with polishing processes. There is some evidence that the lubricant enters into small openings and cracks of the surface and by pressure or otherwise, exerts a breaking-up action as observed by Rehbinder and W. von Engelhardt.

With regard to the suggestion that the coefficient of friction observed in my experiments are not strictly comparable with those observed in pure sliding, I should like to state that two series of tests were carried out, one without abrasive and the other with abrasive. In the case of grinding with abrasive and fluid, the measured friction coefficient is the ratio of tangential to radial cutting force.